

# Liquid Droplet Radiator Development Status

(NASA-TM-89852) LIQUID DROPLET RADIATOR  
DEVELOPMENT STATUS (NASA) 28 p CSCI 22B

N87-20353

G3/18 Unclass  
45388

K. Alan White, III  
*Lewis Research Center*  
*Cleveland, Ohio*

Prepared for the  
22nd Thermophysics Conference  
sponsored by the American Institute of Aeronautics and Astronautics  
Honolulu, Hawaii, July 8-10, 1987



## LIQUID DROPLET RADIATOR DEVELOPMENT STATUS

K. Alan White, III\*  
National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135

### Abstract

Development of the Liquid Droplet Radiator (LDR) is described. Significant published results of previous investigators are presented, and work currently in progress is discussed. Several proposed LDR configurations are described, and the rectangular and triangular configurations currently of most interest are examined. Development of the droplet generator, collector, and auxiliary components are discussed. Radiative performance of a droplet sheet is considered, and experimental results are seen to be in very good agreement with analytical predictions. The collision of droplets in the droplet sheet, the charging of droplets by the space plasma, and the effect of atmospheric drag on the droplet sheet are shown to be of little consequence, or can be minimized by proper design. The LDR is seen to be less susceptible than conventional technology to the effects of micrometeoroids or hostile threats. The identification of working fluids which are stable in the orbital environments of interest is also described. Methods for reducing spacecraft contamination from an LDR to an acceptable level are discussed. Preliminary results of microgravity testing of the droplet generator are presented. Possible future NASA and Air Force missions enhanced or enabled by an LDR are also discussed. System studies indicate that the LDR is potentially less massive than heat pipe radiators. Planned microgravity testing aboard the Shuttle or Space Station is seen to be a logical next step in LDR development.

### Introduction

Future space missions currently being considered by NASA and the Air Force will require power levels far in excess of Space Shuttle or IOC Space Station usage. The development of power systems capable of supplying megawatts or even gigawatts of power has revealed a need for advanced space radiators which can reject the attendant waste heat. Heat pipe radiators, which represent the best of current technology, typically have a specific mass around 5 kg/m<sup>2</sup>. Design refinements and advanced composites may eventually reduce this figure to 2 kg/m<sup>2</sup>.<sup>1</sup> The development of long life advanced radiators will be an enabling technology for realization of multimewatt space missions. Such radiators will be significantly less massive than heat pipe or fin radiator technology in current use.

Several advanced radiator concepts expose the radiating medium directly to the space environment, thus eliminating the mass of piping characteristic of heat pipe radiators. These concepts include moving belt concepts,<sup>2</sup> dust radiators,<sup>3</sup> and the Liquid Droplet Radiator (LDR). The LDR concept is shown schematically in Fig. 1. A

working fluid is heated through a heat exchanger, and is then formed into billions (or trillions) of liquid droplets by a droplet generator. The droplets are focused by the droplet generator to a collector, and travel in space, cooling by radiative exchange with the space environment. The droplet collector captures the droplets, and the working fluid is recycled through the heat exchanger to the droplet generator. The LDR concept was first suggested in 1978<sup>4</sup> as an intrinsic improvement on the dust particle radiator.<sup>3</sup> This paper reviews the development to date of the LDR concept. Development has been funded by AFRPL, NASA (Lewis, Langley, and Marshall), AFOSR, DOE, and by IRAD funding at Grumman Aerospace, Spectra Tech., Inc. (STI), and McDonnell Douglas Astronautics Company (MDAC).

Numerous advantages of the LDR concept, as compared to existing technology, have been suggested. For most applications investigated, the LDR has a lower specific mass than existing technology. The LDR is more readily deployed than existing radiators, as indicated in Fig. 2.<sup>1</sup> A possible deployment sequence for a rectangular LDR (different LDR configurations are described in the next section) is shown. Deployment of a triangular LDR (i.e., one with a focused droplet sheet converging at the collector (Fig. 3)) would likely occur by a similar procedure. Additionally, the LDR offers promise of compact stowage in the Shuttle bay. The active radiating area of an LDR is the surface area of trillions of submillimeter droplets; these droplets collectively have a small volume when condensed into a compact liquid mass. Thus, the LDR is compactly stowed as a result of the high surface area to volume ratio of a submillimeter sphere.

The LDR is relatively immune to damage from micrometeoroids, since only the generator, collector, and any connecting piping need be armored. For similar reasons, the LDR is relatively immune to hostile threats from laser, particle beam or kinetic energy weapons.<sup>5,6</sup> The merits of the LDR are discussed in depth in many papers, especially in the earlier literature.<sup>4,7,8</sup>

This paper discusses the progress achieved to date in the development of the LDR. A number of alternative LDR geometries have been proposed, and these are briefly described and reviewed. Of these options, rectangular and triangular LDR's appear most promising, and are discussed in more detail. The design, testing, and further development of a droplet generator and collector for the rectangular and triangular LDR's are reviewed. Droplet formation constraints and the limitations of current orifice fabrication technology are discussed, and are shown to be an integral part of generator design. A conceptual design of a focused droplet generator is presented. This general design is modular in nature, and can be adapted to ensure reliable operation, even after numerous micrometeoroid encounters. A linear

\*Member AIAA

collector for the rectangular LDR has been designed, fabricated, and tested at Grumman. Successful droplet collection was demonstrated for incident droplet velocities below 6 m/s. Details of the testing, including simulated zero gravity verification, are summarized. A centrifugal collector for a triangular LDR is briefly described.

The behavior and sizing of the droplet sheet has a tremendous influence on component design. Analyses of the radiative behavior of the droplet sheet are summarized, and theoretical predictions are compared with experimental measurements. Colliding droplets in the droplet sheet have been investigated, and experimental and analytical results are presented.

Droplet charging and atmospheric drag affect the droplet sheet, and the findings of analytical assessments of these two issues are presented. The behavior of a droplet sheet exposed to a micrometeoroid shower or to hostile threats is briefly discussed. Identification of a suitable droplet fluid is considered. Stability of the working fluid to atomic oxygen and UV radiation is discussed, and preliminary experimental findings are summarized.

Two other development issues are considered. Proper LDR design must reduce potential spacecraft contamination to an acceptable level. A number of approaches to achieving this are presented. Enclosing the droplet sheet with a material transparent to IR is discussed as a promising solution. Secondly, microgravity testing of the LDR is discussed, and preliminary results of microgravity testing of the droplet generator are presented.

The design of the LDR system is briefly discussed as a basis for estimating LDR specific power. Potential missions enhanced or enabled by LDR technology are briefly reviewed, and the LDR is compared with heat pipe technology. Finally, conclusions and future plans are presented.

#### Alternative Configurations

A number of different LDR geometries have been proposed and evaluated. The spiral LDR<sup>5</sup> employs a generator and collector which rotate at the same angular velocity. Droplets ejected from the generator traverse a spiral trajectory, and are then collected. A related concept, the enclosed disc LDR,<sup>5</sup> also contains a droplet generator at the center of a disc of radiating droplets. In the enclosed disc LDR, only the collector rotates. The droplet sheet is a thin disc of droplets, with a disc radius equal to the distance between droplet generator and collector. The entire radiator is enclosed by a transparent shroud, which minimizes spacecraft contamination resulting from any errant droplets. A third variation, the annular LDR,<sup>5</sup> utilizes a rotating collector to capture an annular sheet of droplets from an annular generator. At least two detailed evaluations of the spiral, disc, and annular LDR configurations have been conducted.<sup>5,6</sup> The relative merits of these three concepts, as well as other concepts discussed below, were considered. The annular LDR was disregarded because of inefficient radiative performance - the sheet radiates to itself more than the droplet sheets of alternate configurations. The disc and spiral LDR geometries were also eliminated. A consensus

opinion was that these concepts were more complex, due to unnecessary rotation of the collector. Other factors were considered in eliminating these concepts; these are discussed elsewhere.<sup>5,6</sup>

Several proposed variations of the LDR utilize electric fields to control droplet trajectories. Use of an electric field for such a purpose has had commercial success in the Ink Jet Printer market, where droplet charging and subsequent electrostatic deflection is routine. The electrostatic thermal radiator (ETHER)<sup>9</sup> is essentially a proposed variation of the LDR. The droplets are formed by conventional means, and are subsequently charged. As a result of an applied charge on the spacecraft that is opposite the droplet charge, the droplets will execute a slightly elliptical orbit. This closed trajectory would allow a droplet generator and collector to be closely located on a spacecraft, thereby eliminating structural and piping mass. The proposed ETHER concept has not been further investigated, due to concerns about droplet-plasma interactions. Applying and maintaining a steady charge on a spacecraft in low earth orbit is also a significant technological barrier, since the spacecraft will acquire its own potential.

The utilization of magnetic fields to control droplet trajectories has also been investigated.<sup>10,11</sup> This option is discussed as an alternate collector concept later in this paper.

Rectangular and triangular versions of the LDR have been investigated most extensively. The rectangular LDR, shown in Fig. 2, employs a linear collector which is as wide as the droplet generator. The collector can be two sided, as shown in Fig. 2, where two droplet sheets traveling in opposite directions impact a single collector. An alternate variation would utilize a one sided collector, with only one generator and droplet sheet. In a rectangular LDR, there is no focusing of the droplet sheet, and the droplet number density remains constant along the flight path. Several collector concepts for a rectangular LDR have been proposed. One of these has been investigated experimentally and analytically at Grumman.<sup>1,12</sup> The triangular LDR concept, shown in Fig. 3, employs a droplet generator to form a converging array (sheet) of droplets. The collector, located at the convergence point of the droplet sheet, employs a centrifugal force to capture the droplets.

The relative merits of the rectangular and triangular configurations have been considered in detail by researchers at the University of Washington (UW), Mathematical Sciences Northwest (MSNW, now known as STI), Grumman, McDonnell Douglas, NASA Lewis, and the Air Force Rocket Propulsion Laboratory (AFRPL). The triangular LDR is inherently less massive, because of the smaller collector possible with a focused sheet. Recent system studies have indicated that a triangular LDR can be 40 percent less massive than a rectangular LDR. Nevertheless, there are compelling reasons which argue for a consideration of a rectangular LDR. The droplet generator is less complex for a linear collector, since it is not required to generate a focused droplet sheet. For any sheet width and length, a rectangular sheet has twice the area of a triangular sheet, and therefore a rectangular LDR can reject more

heat. Additionally, it was originally recognized that a centrifugal collector might be more complex than a linear collector, as the rotating collector might require rotating fluid couplings. That is, complex rotating seals which would operate in a zero gravity environment were thought to be required. However, the use of pitot tube pickups to eliminate such rotating seals has been successfully demonstrated, and is discussed later.

For the reasons discussed above, it was observed that the rectangular and triangular options both had considerable merit. A parallel development effort of the centrifugal and linear collectors thus ensued. A number of critical issues in the development of the triangular LDR have been partially or totally resolved. For example, a feasible conceptual design of a focused droplet generator has been suggested. Similarly, the use of pitot pickups eliminates the need for complex rotating seals. Thirdly, collisions in a focused droplet sheet result in coalescence of the impacting droplets. These issues are discussed later in more detail. Since these feasibility issues are apparently resolvable, the triangular LDR is now being developed more extensively. Although development of the linear collector is not being funded at present, it has not been eliminated from further consideration. Unforeseen barriers to the successful demonstration of a triangular LDR may lead to a renewed interest in the linear collector at some future date.

#### Droplet Generator Development

Many stringent requirements are placed on the design and operation of the droplet generator. The generator must create a well-defined three-dimensional array of droplets. A point design of an LDR (rejecting 6.3 MW) computed droplet sheet mass, component masses, structural mass, and the mass of pipe and pumps.<sup>5</sup> For this example, the droplet generator represented 15 to 20 percent of the total radiator mass, depending on the droplet radius assumed. Minimizing droplet generator mass will thus have a significant impact on total radiator mass. Similarly, point designs for typical LDR missions have indicated that between  $10^5$  and  $10^7$  droplet streams are typically required. For a megawatt radiator, each stream might contain  $10^5$  droplets. Requirements on droplet velocity are still being investigated, but a range of 3 to 30 m/s for each of the  $10^{10}$  to  $10^{12}$  droplets appears reasonable. Similarly, 50 to 500  $\mu\text{m}$  diameter droplets are required.

Droplet aiming requirements for an LDR droplet generator have been systematically investigated.<sup>5,6</sup> Although generating precisely aimed droplet streams is a generator requirement, collector mass is appreciably altered. Preliminary LDR system mass studies indicate that collector mass begins to become a significant fraction of total LDR mass only when the aiming accuracy approaches 10 mrad.<sup>5</sup> Thus, improving the aiming accuracy from 10 mrad to perhaps 2 mrad does not significantly improve total LDR mass, although collector mass is reduced substantially. The critical requirement on generator aiming is that no droplet stream miss the collector. With  $10^5$  droplet streams, misdirection of one stream yields a mass loss in two weeks approximately equal to the mass of the entire droplet sheet.<sup>5</sup>

The major impact of generator aiming may be on the radiative performance of the droplet sheet. Although this effect has not been quantified, better aiming accuracy obviously will reduce the number of droplet collisions within the sheet. The collision and coalescence of two droplets reduces their combined area by 21 percent. Therefore, a large number of droplet collisions will reduce the radiative effectiveness of the droplet sheet. Hence, the aiming requirement of the droplet generator should be as stringent as current fabrication technology will allow.

A number of techniques have been considered as candidate methods for forming trillions of droplets of uniform velocity and diameter. Of these, breakup of a liquid jet by application of an imposed periodic disturbance is most satisfactory. Rayleigh breakup of a liquid jet has been employed to produce up to 250 000 droplets per second from a single orifice.<sup>13</sup> All continuous Ink Jet Printers work on this concept, and details of jet breakup into uniform droplets have been reported extensively in the literature.<sup>14</sup> In LDR development to date, droplet generation has been demonstrated experimentally by researchers at STI,<sup>5</sup> UW,<sup>15</sup> Grumman,<sup>12</sup> the University of Southern California (USC),<sup>16</sup> and NASA Lewis.<sup>17</sup> Most work has been with low vapor pressure oils. Droplet formation using mercury was investigated very briefly at UW,<sup>15</sup> to ascertain the effects of high surface tension (low Weber number). Droplets of mercury were generated, but no significant conclusions could be drawn.

Droplet formation has been investigated extensively at NASA Lewis, both experimentally<sup>17</sup> and analytically.<sup>18,19</sup> Droplets ranging from 60 to 1000  $\mu\text{m}$  diameter have been generated from single and multiple hole orifices of 33 to 200  $\mu\text{m}$  diameter. Uniform droplet formation occurs over a wide range of stimulation frequencies. The generator operating regime in which uniform droplet formation occurs is a function of frequency, droplet velocity, and fluid properties such as viscosity and surface tension.<sup>17</sup> Orifice geometry has little or no effect on droplet formation. The formation regions observed at NASA Lewis agree qualitatively with numerous other investigations, although slightly wider operating regions were observed at NASA Lewis than elsewhere. This is apparently due to square wave pulsing (rather than the more common sinusoidal) of the piezoelectric stimulator. This is currently being investigated at NASA Lewis. The droplet formation regions are being defined in terms of appropriate dimensionless groups, so as to be applicable to any LDR fluid of interest.

The coupling of imposed periodic waveforms with the resulting capillary instabilities observed prior to jet breakup has been investigated in detail.<sup>18</sup> The imposed periodic waveform is generally a sinusoidal voltage signal which is used as input to a piezoelectric transducer. The output of the transducer is a dynamic pressure variation, which generates capillary instabilities on the liquid jet. The regions of convective and absolute instability of a liquid jet have also been investigated analytically for inviscid<sup>18</sup> and viscous fluids.<sup>19</sup> A comparison of experimental and analytical results is in progress.

Droplet stream stability over flight paths of tens or hundreds of meters is of great concern in the LDR development program. In order to prevent intra-stream droplet collisions, the variance in individual droplet velocities must be small. Researchers at USC have experimentally investigated intra-stream velocity dispersion, which is the ratio of variance in velocity to the average droplet velocity. The experimental apparatus is described in detail elsewhere.<sup>16</sup> When a conventional sinusoidal disturbance is applied to the piezo, velocity dispersion<sup>20</sup> is around  $10^{-5}$ . A significant finding has been in the application of an amplitude modulated sinusoidal waveform to the piezoelectric transducer. The basic carrier waveform was a sinusoidal carrier wave with a frequency between two and eight times the frequency of the modulation sinusoid. If this ratio is denoted as  $N$  ( $N = 2, 3, \dots, 8$ ), velocity dispersion was observed to decrease as  $N$  is increased.<sup>14,16</sup> Further research (unpublished) revealed a functional dependence of  $1/N$  between velocity dispersion and  $N$ .

An order of magnitude reduction in velocity dispersion may have a significant impact on the behavior of the droplet sheet. This can be seen in Fig. 4, which is discussed in more detail elsewhere.<sup>21</sup> Figure 4 shows the distance that a droplet stream can travel before significant merging has occurred. For a typical LDR flight path of 100 m, velocity dispersions below  $10^{-6}$  are required. Dispersions of  $5 \times 10^{-7}$  in a single stream have been demonstrated.<sup>16</sup> Thus, using a properly designed droplet generator, droplet streams could travel 100 m in an LDR without significant merging from intra-stream collisions.

Several point designs of an LDR droplet generator have indicated that the mass of fluid in the generator is a dominant percentage of the generator mass.<sup>5,22</sup> Current research is devoted to minimizing the size and mass of the generator,<sup>23</sup> and thus of the makeup working fluid within the generator. Previous droplet formation studies at NASA Lewis<sup>17</sup> and USC<sup>16</sup> have utilized an acoustic cavity upstream of the orifices. A piezoelectric transducer is either immersed in the cavity, or separated from the cavity by a diaphragm, and a pressure waveform is thereby applied to the jets issuing from the cavity. Cavity acoustics indicate that the cavity must be at least half a wavelength long, where the wavelength in question corresponds to the desired excitation frequency. For conditions of interest to the LDR, a cavity dimension of 14 cm is indicated. This is undesirable for a low mass generator. An alternate approach is to mount the piezo on the downstream side of the orifice plate, thereby eliminating the need for an acoustic cavity. Preliminary results indicate that velocity dispersions in such a design are comparable to those observed earlier.<sup>23</sup> Measurement of velocity dispersion in a 100-orifice array of jets issuing from such a generator is currently in progress.

The fabrication of thousands of high quality micro-orifices was identified early as a critical technology issue. At least nine fundamentally different orifice fabrication methods have been identified: laser drilling, electrodischarge machining (EDM), electrochemical milling (ECM), mechanical drilling, mechanical broaching (punching), electron beam machining (EBM),

electroforming (chemical milling), ion drilling, and the drawing (pulling) of soluble core glass fibers. The first four of these methods were evaluated as candidate technologies.<sup>5,15,17</sup> Based on this evaluation, NASA Lewis decided to develop mechanical drilling in-house. It was later discovered that electroforming is utilized by several Ink Jet Printer manufacturers to fabricate orifice plates with trajectory accuracies comparable to or better than those possible with mechanical drilling. However, due to a low aspect ratio limitation of chemical milling, it was realized that generator design would be complicated if the electroforming technology were relied upon.

In-house development of mechanical drilling at NASA Lewis was initially focused on choosing the optimum orifice geometry. Ease of machining, the desire for high discharge coefficients, and several other factors were considered.<sup>17</sup> The geometries investigated are shown in Fig. 5. The chamfered geometry (minus the protruding lip) of Fig. 5 was chosen for further development. Fabrication of such a profile is a two step process. A conical entry is first machined. The second step involves drilling the final orifice diameter. The orifice length to diameter ratio is variable, but is typically between one and two. Two critical issues arise in this machining process. One involves the removal of burrs from the orifice after the final drilling operation. This issue has been largely resolved. The second critical problem in mechanical drilling is the proper alignment of the drill in the conical inlet. Radical improvements have been made since 1983, and this issue has also apparently been resolved. A one step process to fabricate the geometries described above has also been considered. It appears to actually be more complex than the two step process described above. The details are arcane in nature, and will not be discussed here.

Determination of aiming accuracy of fabricated orifice arrays has not received enough attention to date. Before the orifice fabrication process can be realistically evaluated, two complicating factors must be accounted for. First, deflection of the orifice plate, due to a pressure difference across it, must be minimized and corrected for. This is relatively straightforward. The presence of a film on the downstream surface of the orifice plate adversely affects the jet trajectory. Examination of a single jet has revealed that the jet deviates from its intended trajectory when a liquid film is present at the orifice exit. The deviation is less pronounced as jet velocity increases. Compensating for this effect has proven difficult to date, since the effect is immensely complicated with an array of closely spaced orifices. An engineering estimate of the trajectory accuracy of the best orifice arrays produced by mechanical drilling is 3 mrad. Proper measurement and evaluation of orifice array performance is an area of considerable importance to continued LDR development. Therefore, techniques for more accurately measuring jet straightness are currently being investigated at NASA Lewis.

The development of mechanical drilling at NASA Lewis has become a reasonably mature technology. Nevertheless, it is worthwhile to reconsider the relative merits of the various methods

of orifice fabrication. Considerable improvements in EDM have occurred since 1983, spurred on by the requirements of several Ink Jet Printer manufacturers. A second evaluation of the most suitable technology is now in progress.

With the fabrication limitations and restrictions on droplet generation known, a realistic design of a droplet generator can be considered. It is apparent that some degree of segmenting, or modularization, will be required. For a generator with  $10^6$  orifices, fabrication of the orifices alone would require 2 yr of continuous mechanical drilling, given present technology. Other competing fabrication methods, notably electroforming, may be more rapid, but this has not been investigated. Modularization will eliminate the possibility of a single point failure. It will also allow for more rapid production of  $10^6$  orifices, if parallel production stations are utilized. The unknown, at present, is the degree of segmentation to be employed. This issue is being actively investigated.

A generator concept which considers the limits of current fabrication technology is shown in Fig. 6. This is ideal for a triangular LDR; for a rectangular LDR, the arc would be pulled straight. The optimum ratio of sheet length to sheet width depends on numerous factors, and is discussed later in this paper. The arc is actually composed of individual generator modules. The fluid manifold connecting each module is designed such that each is at the same pressure.<sup>5</sup> A valve will be located in each module to remove the module from operation in the event of module failure. This will eliminate one single point failure mode of the droplet generator. Each module contains an array of orifices fabricated in a flat substrate. Each array can be two-dimensional. The array would typically contain between 12 and 30 rows of orifices. The number of rows in an array is equal to the number of layers in the droplet sheet; the number of layers is mission dependent, and has not been totally resolved. The number of orifices in each row is dependent on the orifice fabrication limitations. For example, if 5000 orifices can be routinely fabricated in an array, there would be 160 to 420 orifices in each row. If the orifice fabrication process is more suited to producing linear arrays, then each module would have between 12 and 30 different orifice plates, each containing perhaps 200 to 1000 orifices.

The design of Fig. 6 is very general in nature; specific details of the design are strongly dependent on heat rejection load and temperature. The mass of the generator is influenced by the configuration of the pulsing device. If a resonant cavity configuration can be avoided, the generator will be less massive. Direct stimulation of the individual orifice arrays is a focus of current research at USC.<sup>23</sup> Another concern in the design of a generator is the influence of orifice plate wetting (in orbit) on the jet trajectories. This is being evaluated at present in the NASA Lewis Zero Gravity Facility, and is described later.

If wetting does prove to adversely affect generator performance, there are several approaches that can be taken. Nonwetting coatings could be applied to the exit side of the orifice array

prior to orifice fabrication. This was investigated briefly at NASA Lewis.<sup>17</sup> TEFLON and FREKOTE coatings were successfully applied to aluminum plates prior to drilling the orifices. High quality orifices could not successfully be fabricated in these coated plates. Application of a nonwetting coating after orifice fabrication does not appear viable, as the coating tends to plug the micro-orifices. Another approach is to control the potentially adverse effects of wetting through a specially designed shear sealing valve. This design would utilize an optically smooth (maybe 0.0001 rms surface finish) cover plate over the orifice plate. At generator startup or shutdown, the cover plate, controlled by a solenoid valve, would move into the appropriate position. Grumman Aerospace has applied for a patent for this concept.

For a liquid metal droplet generator, the design of Fig. 6 might require modification. Available piezoelectric or magnetostrictive materials do not possess Curie points compatible with liquid metal operation. Active cooling of the piezo elements will likely be satisfactory for the lower temperature range of liquid metal operation. For higher temperatures, the feasibility of active cooling is unknown. Alternate approaches proposed by Grumman and MDAC may be further investigated; these concepts are proprietary at present.

For a focused droplet sheet of a triangular LDR, the design of Fig. 6 considers the limitations of current orifice fabrication technology. Orifices are fabricated in flat surfaces, and the jets from an individual module are all parallel. The opening of the droplet collector is thus approximately the same width as that of an individual generator module. Focusing of the droplet sheet is achieved by a proper orientation of the generator modules. An alternate approach, in which generator focusing is achieved by mounting a flexible orifice substrate on a curved manifold,<sup>5</sup> appears to be much more susceptible to micrometeoroid damage, as a result of the much thinner orifice substrate which would be required.

A recently proposed alternative advanced concept, the Liquid Sheet Radiator (LSR), would greatly simplify design of the droplet generator.<sup>24</sup> The LSR concept is closely related to the LDR concept, and would replace the trillions of droplets with continuous triangular liquid sheets. Generator focusing to a point collector is thus achieved automatically in the LSR concept, and thousands (or millions) of orifices are no longer required. Preliminary analytical and experimental results have demonstrated the feasibility of the LSR concept,<sup>24</sup> but further research is required.

#### Droplet Collector Development

Design and development of an LDR droplet collector has been complicated by the lack of similar commercially available technology. Droplet collectors (gutters) for Ink Jet Printers generally rely on electric fields. A similar approach for an LDR is very complex, due to the nature of the space plasma and solar wind. A droplet collector for the LDR must collect essentially all incoming droplets. To achieve an acceptable mass loss over a 30 yr lifetime, acceptable collector

loss rates are of the order of 1 lost droplet per  $10^8$  incident droplets. After capturing the droplets, the collector must develop a sufficient pressure head to pump the liquid back to a heat exchanger. This must be accomplished in zero gravity, without the benefits of a gravity head or an ambient gas pressure.

A number of collector alternatives were conceived by investigators at the University of Washington. These are described in more detail elsewhere.<sup>5</sup> Briefly, the concepts are:

- (1) Centrifugal collector (four different concepts)
- (2) Surface entrainment collector
- (3) Passive collector with a diffuser-shaped inlet
- (4) Moving belt collector
- (5) Electrostatic collector
- (6) Rotating spiral collector
- (7) Surface tension collector

The first two concepts have been investigated most extensively, and are described in detail later. The remaining five concepts are generally regarded as less promising,<sup>5,6,12</sup> and have not been pursued in detail.

Other concepts have also been considered. McDonnell Douglas briefly investigated a collector based on electrophoretic and dielectrophoretic forces.<sup>6,25</sup> Such a concept, as well as the electrostatic collector<sup>5</sup> and the electrostatic thermal radiator (ETHER),<sup>9</sup> have not been considered further, due to concerns about charging and discharging of droplets in the space environment.

Use of magnetic fields to capture droplets and control droplet trajectories was investigated experimentally and analytically.<sup>10,11</sup> A cobalt-samarium magnet was used to magnetize a ferrofluid, and control of droplet trajectories was demonstrated. The influence of magnetic field strengths up to 3 kG (0.3 T) on droplet capture was also examined. At sufficiently high field strengths, droplet splashing at a simulated collector surface was totally suppressed. This is demonstrated in a series of fascinating and conclusive photographs.<sup>10,11</sup> A full-scale magnetic LDR using superconducting electromagnets was conceived, and system studies comparing a magnetic and a conventional LDR were carried out. Total radiator mass was heavier, in many cases, for a magnetic LDR, owing to massive electromagnets. For this reason, and because of additional development challenges, a magnetic LDR has not been investigated further.

The advantages of the rectangular LDR discussed earlier necessitated development of a linear collector with a width equal to that of the droplet generator. A passive collection scheme conceived at the University of Washington<sup>5</sup> was developed at Grumman,<sup>1,12</sup> and is shown in Fig. 7. The collector has an opening slightly larger than the thickness of the incident droplet sheet. An auxiliary film can be injected on both surfaces of the collector. The incident droplet streams impact the flowing film, and the total liquid flow directly feeds a gear pump. The collector and its associated pump are shown conceptually in Fig. 8.

A sub-scale linear collector was fabricated and tested in vacuum under a variety of operating conditions.<sup>12</sup> The droplet sheet from a droplet generator impacted a collector surface at angles from 2 to 90°. The generator and collector, in combination, could be oriented at different angles to the gravity vector; testing was always conducted at two substantially different angles to assess any effects of gravity on collector operation. Diagnostics allowed detection of droplet loss rates of 1 in  $10^8$ . A series of tests with both 4 and 30 droplet streams served to define collector operating regimes where measured loss rates were less than 1 droplet in  $10^8$ . These operating regions are given for a range of droplet velocities, for angles of incidence (between droplet streams and the collector surface) from 2 to 90°. Acceptable collector performance was observed for all droplet velocities below 6 m/s. In some instances, droplet streams traveling at 20 m/s were successfully captured.<sup>12</sup> Since none of the test results were affected when the orientation of the apparatus with respect to the gravity vector was changed, it is concluded that the linear collector will successfully capture droplets in microgravity.

It was discovered that the primary loss mechanism was not from rebounding droplets. Rather, secondary droplets smaller than the incident droplets were lost as a result of wave shedding. The impacting droplet streams formed a fluid film on the collector surface, and waves were observed on the surface of the film. Secondary droplets were released from the crests of these waves.

Droplet streams impacting the collector surface occasionally created a backflow on the surface. This phenomenon is illustrated in Fig. 7. The film created on the collector surface usually flowed in the desired direction, toward the collector gear pump. Sometimes, the film flowed away from the pump. An auxiliary film could be injected on the collector surface, upstream of the droplet impact zone, as shown in Fig. 7. When an auxiliary film was injected, backflow on the collector surface was no longer observed.

Proper operation of a collector pump in zero gravity is a second critical issue of collector development. Peristaltic, cystaltic, trochoid, and gear pumps have been evaluated; a positive displacement gear pump appears best suited for this application. For the collector shown in Figs. 7 and 8, the liquid feeds directly into the gears, in order to minimize viscous losses. A series of experiments was conducted to determine the input pressure to the gear pump as a function of the pertinent quantities. A recovery coefficient of 0.18 was obtained.<sup>12</sup> Analysis indicates that an auxiliary film could improve this low pressure recovery coefficient, and an auxiliary film might be required for proper operation of the gear pump. Collector operation with 900 incident droplet streams was demonstrated. When the gear pump was not powered, severe splashing was observed at the mouth of the pump; when electrical power was supplied to the pump, splashing was not observed. Because of limitations of the droplet generator and the orifice plate, precise loss rates could not be measured diagnostically.

The lower mass inherent in a centrifugal collector has prompted a parallel evaluation of this concept. Centrifugal collection in microgravity has previously been demonstrated for a waste collection system on Skylab. Of at least four different centrifugal collectors originally conceived,<sup>5</sup> the rotating shroud collector has been the only concept investigated. The incident droplet streams impact a cone shaped target of the collector (Fig. 9), and a liquid film migrates radially outward. Any droplets that rebound off the spinning cone are collected by that portion of the shroud extending in front of the target. This fluid migrates to the front of the collector by virtue of a slight taper of the shroud, and as a result of the centrifugal force. The liquid is collected by means of stationary scoops which are immersed in the rotating pool of liquid. These scoops are actually pitot pumps, and their operation is similar to the operation of a pitot probe used for local velocity measurement of a liquid or gas stream.

An initial evaluation of the concept was carried out by investigators at the University of Washington and Mathematical Sciences Northwest (MSNW).<sup>5</sup> A flat plate rotated between 0 and 1650 rpm. The center of the flat plate was of a porous material, which allowed an auxiliary film to be injected. This film flowed radially outward, aiding in droplet capture. A single droplet stream was incident on the rotating plate, and no splashing of the incident droplets was observed visually. Detection of secondary droplets, such as Grumman observed in their testing of a linear collector, was not possible visually, and remains to be investigated. An analysis of the film flow predicted the formation of surface waves in normal gravity operation. The experimental observations could not be compared with this analysis, since the film did not evenly wet the surface of the rotating plate. Similarly, interactions of the incident droplets with the surface waves could not be investigated. The use of an array of small diameter tubes protruding toward the incident droplet streams has been suggested as a method for eliminating surface waves, but this has not been demonstrated.

A parallel effort has examined splashing from different surfaces.<sup>5</sup> Droplet streams impacted on ordinary surfaces, on screens of varying mesh number, and on closely-spaced parallel wires. It was found that the use of a proper screen target can reduce splashing by a factor of 500 or more, compared to a flat plate. Velocities were between 8 and 18 m/s, representative of velocities in an operational LDR. These findings are of obvious importance in collector design.

A more extensive evaluation of the centrifugal collector is currently in progress at MDAC, Spectron Development Labs, and Spectra Technology. The pitot tube pickup has been evaluated as a suitable method for fluid recovery. At 300 rpm, ~5 psi was developed by a pitot probe. This angular velocity is sufficient to develop a 20 g centrifugal force at the collector periphery. Thus, gravitational forces will be minimal, but operation will nevertheless be demonstrated in a series of zero gravity tests. Collector operation will be demonstrated with an array of 450 droplet streams.

## Development of Auxiliary Components

In addition to a droplet generator and collector, an LDR will consist of a structure supporting the collector, a pipe for fluid return from the collector to the generator, various pumps, a heat exchanger to reheat the working fluid, and gimbaling devices to maintain proper LDR orientation with respect to the spacecraft, sun, and earth.<sup>26</sup> These auxiliary components have received little attention, due to an already established technology base in the aerospace industry. The mass of such components has generally been included in LDR system mass calculations.<sup>5,6,17,26</sup> It has been recognized that an active alignment and pointing system will be required to maintain the proper orientation between droplet generator and collector. A preliminary design<sup>6</sup> borrows from existing technology, and will overcome small positional changes resulting when the LDR is deployed in orbit. Refinements to this design have been made by MDAC, but are considered proprietary at present.

The mass of the necessary structure and of the fluid return pipe can be quite significant, and the use of parallel LDR's has been proposed<sup>4</sup> as a solution. It has been found that two LDR's configured as shown in Fig. 10 are often lighter than one,<sup>7,22</sup> since fluid return lines and interconnecting structure are eliminated. A fluid return line is subject to a single point failure, and is therefore massive, as it must be protected from micrometeoroids. A conventional truss structure, as shown in Fig. 3, is satisfactory.

## Radiative Behavior of Droplet Sheet

A meaningful comparison of the LDR with other advanced concepts, including heat pipe radiators, depends on a knowledge of the heat rejected by the droplet sheet. An exact analysis of the radiation from a sheet of billions or trillions of droplets is intractable. In addition to a transient behavior which is a function of all three coordinates, every droplet is nonisothermal, possessing a temperature gradient which is also a function of all three coordinates. All analyses to date have neglected temperature gradients within a droplet. Since sheet width is much greater than sheet thickness, temperature gradients along the width of the sheet are insignificant compared to gradients across the sheet thickness, or along the sheet length (direction of droplet travel). All analyses to date have also made this assumption. Also, variations in optical properties with decreasing droplet temperature have also been ignored. Finally, a triangular droplet sheet has been difficult to analyze, due to a constantly changing droplet number density.

The initial work in analyzing radiative behavior of the droplet sheet was done by Mattick and co-workers.<sup>4,27</sup> The droplet sheet geometry was characterized by  $\tau$ , the optical depth. Mattick defined  $\tau = N\sigma S$ , where  $N$  is the droplet number density per unit volume,  $\sigma$  is the projected cross sectional area of a droplet ( $\sigma = \pi R^2$ ), and  $S$  is the sheet thickness. The  $N\sigma$  product is thus an estimation of the extinction coefficient. With  $\tau$  defined in this way, the transmission through a sheet of black



droplets is simply  $e^{-\tau}$ . By considering the relevant equations of radiative transfer,<sup>4,27,28</sup> a numerical procedure is utilized to relate hemispherical sheet emittance to optical depth and droplet emissivity,  $\epsilon_0$ . Isotropic scattering was assumed in the initial analysis,<sup>7</sup> and forward and backward scattering were included in later work.<sup>27,28</sup> The effects of forward and backward scattering on sheet emittance can be seen in Fig. 11.<sup>27</sup> Figure 11 indicates that, for sufficiently large sheet optical depths, the sheet emittance can be significantly larger than the droplet emissivity. Radiative power can vary 12 percent, depending on whether forward or backward scattering is assumed.

A knowledge of temperature distributions within the sheet is required for proper insight into the radiative performance of the sheet. Mattick and Hertzberg<sup>29</sup> considered temperature variations across the sheet thickness, neglecting gradients along the width or length of the sheet. The analysis further assumed an LDR where the average droplet temperature at the collector is 80 percent of that at the generator. Temperature profiles of such a droplet sheet are presented. The change in sheet emittance with path length is also presented. Although the average droplet temperature decreases 20 percent over the sheet length, the sheet emittance decreases by 4 percent or less for the range of optical depths and droplet emittances studied.<sup>29</sup> A more precise and extensive analysis of these effects has been conducted at NASA Lewis,<sup>30-33</sup> and is discussed later.

Experimental verification of these results has been carried out by a number of researchers at UW. The experimental apparatus is described in detail elsewhere.<sup>27,34-36</sup> To examine higher optical depths, radiation from a cylindrical cloud of droplets was investigated. The initial experiments utilized an array of 175  $\mu\text{m}$  orifices, with the 465 orifices arranged in a series of concentric circles. By varying droplet diameter and intra-stream droplet spacing, diametrical optical depths between 0.9 and 1.8 were examined. Subsequent experiments were with a 2300-hole array of 175  $\mu\text{m}$  orifices, and optical depths between 2.0 and 2.8 were examined. Optical depth was calculated by measuring the attenuation of a laser beam by the cylindrical cloud of droplets.<sup>34</sup> Radiative transfer from the droplet sheet was measured with a thermopile detector.<sup>34,35</sup> Figure 12 shows the experimental results<sup>27</sup> for optical depths between 0.9 and 1.8. Similar results are reported for  $\tau$  between 2.0 and 2.8.<sup>36</sup> It can be observed in Fig. 12 that agreement between experiment and theory<sup>28</sup> is quite good. Droplets of DC-704 between 300 and 500  $\mu\text{m}$  diameter were used experimentally. Since the emittance of a 600  $\mu\text{m}$  droplet of DC-705 was known from a previous experiment,<sup>15</sup> this value of  $0.61 \pm 0.05$  was assumed for 300 to 500  $\mu\text{m}$  droplets of DC-704. The two fluids are very similar chemically, and their optical properties are similar as well. Since droplet emittance is actually a significant function of droplet radius (as discussed later), and since different fluids were used, the data spread of Fig. 12 is to be expected.

Further insight into the radiative characteristics of an LDR droplet sheet can be gained through a Monte Carlo analysis. Of considerable importance to the design of an optimum LDR is

the proper choice of droplet spacing; droplet sheet thickness, width, and length; and droplet velocity. Brown and Kosson<sup>12,37</sup> determined the contribution of various layers of a droplet sheet to the sheet emittance. For a droplet sheet 10 layers thick, the outer two layers contribute almost 40 percent of the total emissive power of the sheet, while the two innermost layers contribute only 10 percent. The droplets in this case each have an emittance of 0.2, typical of liquid metal droplets in the size range of interest, and intra-stream spacing is as close as physically possible. Changing the spacing between droplet layers (in the direction normal to the plane of the sheet) does not affect the sheet emittance, somewhat surprisingly.

A very important result of the analysis is shown in Fig. 13, which is somewhat analogous to Fig. 11. Sheet emittance as a function of droplet emittance and  $\phi$  is shown. Here,  $D$  is the droplet diameter,  $S$  is the space (clearance) between two droplets, and  $N$  is the number of droplet layers. The minimum value for  $S/D$  is unity. This minimum is observed experimentally for Rayleigh jet breakup, and corresponds to a droplet pitch to diameter ratio of two. Fig. 13 indicates that a point of diminishing returns is reached for values of  $\phi$  larger than three to five (dependent on droplet emittance). To minimize intra-stream velocity dispersion, values of two or three for  $S/D$  may need to be considered. Thus, a full-scale LDR may have between 12 and 80 layers, although a droplet sheet 30 layers thick appears to be a practical upper limit for the values of droplet emittance of most interest. The incremental mass penalty associated with adding an additional droplet layer to the generator of Fig. 6 is small. Therefore, a droplet sheet 12 to 30 rows thick appears to be a reasonable compromise between low generator mass and maximum sheet optical depth.

Monte Carlo methods have also been utilized in MCDROP, the McDonnell Douglas LDR system computer code. Isotropic scattering is again assumed. MCDROP can accept as inputs four parameters that describe radiator environment: orbit height, the angle of inclination of the orbital plane to the ecliptic plane, spacecraft location (with respect to the sun) in the orbital plane, and the orientation of the droplet sheet with respect to the ecliptic plane. With these four parameters known, the earth and solar albedos are fixed, and the radiative environment of the LDR is therefore prescribed. Temperature gradients across the sheet thickness are considered. The effects of incident solar and earth radiation on such temperature gradients are presented<sup>26,38</sup> to show the importance of proper LDR sheet orientation with respect to the sun. Even with the LDR sheet edge on to the sun, a nonsymmetric temperature distribution will exist. This is due to both solar radiation reflected from the earth, and emission from the earth.

Recent work at NASA Lewis has extended the earlier work at UW, Grumman, and MDAC. Temperature distributions across the sheet thickness, and along the droplet flight path, have been investigated.<sup>30-33</sup> Isotropic scattering is assumed, and temperature gradients within a droplet are ignored, as are gradients along the sheet width. The relevant equations were solved

numerically, and the results of Mattick<sup>7,29</sup> are presented and extended. The effects of a two-dimensional temperature distribution on sheet emittance and radiated heat load are presented.

All previous analyses have assumed either an isothermal sheet or a one-dimensional temperature distribution with thickness. Sheet emittance is observed to decrease slowly with time (or distance), until a new, lower value of emittance is approached asymptotically. Regardless of the optical thickness or scattering albedo, this steady state sheet emittance is attained at a characteristic dimensionless time.<sup>30</sup> This time corresponds to the sheet losing approximately 30 percent of its initial thermal energy by radiative cooling. This characteristic steady state value of sheet emittance is derived in a steady-state analysis,<sup>31</sup> and results are in complete agreement with those of the transient solution.<sup>30</sup> The steady state value depends only on droplet emittance, optical thickness, and scattering albedo. Finally, the temperature gradients with sheet thickness and length are given as functions of optical thickness and scattering albedo.

The variation of droplet temperature with depth into the sheet results from exterior droplets cooling more rapidly than interior droplets. For liquids whose viscosity varies rapidly with temperature, this temperature distribution would result in droplet streams of widely different viscosity impacting a collector. If the droplet generator produced droplet layers at varying velocities, a more uniform droplet sheet could be produced. Droplet temperature would vary only with distance from the generator. The initial velocity profile required to achieve this is presented in Ref. 32.

Droplet sheet mass for a given heat load is often reduced if solidifying droplets are utilized. The solidifying LDR exploits the latent heat of freezing of the working fluid. The concept has been analyzed by several investigators.<sup>4,33,37,39</sup> The droplet collector may become more complex, since solid droplets impact the collector. If an auxiliary film is injected at the collector, the incoming droplets can be rapidly melted. For a multiple pass LDR, such as in Fig. 10, the close proximity of the collector and heat exchanger allows a heated auxiliary film from the heat exchanger to be injected at the collector. Total LDR mass for a solidifying, parallel configuration has not been evaluated to date.

Although a triangular LDR is presently regarded as more promising than a rectangular LDR, the radiative behavior of a converging droplet sheet is less well understood. The extinction coefficient increases in a complex manner with droplet flight time, mainly due to focusing of the sheet. Both interand intra-stream droplet collisions increase with distance from the generator, decreasing the total number of droplets, but increasing their diameter. As discussed later, the colliding droplets coalesce for the impact velocities expected in a focused sheet. Approximations have indicated that radiation from a triangular sheet may be only 10 to 15 percent less than from a rectangular sheet of equal width and length.<sup>6</sup> This is due to the approximately  $T^4$  behavior, resulting in substantially more

than 50 percent of the radiation being dissipated in the first half of a rectangular sheet. It has been suggested<sup>40</sup> that the effective temperature of a triangular sheet be estimated as the geometric mean of generator and collector temperatures. A better understanding of radiation from a triangular droplet sheet is required, and various investigators are working to that end.

All of the analytical solutions described above rely on knowledge of the droplet emittance. For opaque liquids such as liquid metals, radiation from a liquid droplet is primarily a surface phenomenon. For nonopaque oils, radiation from a droplet is volumetric in nature. The relation between droplet emittance (droplet surface emissivity) and the intrinsic properties of a liquid is derived from fundamental principles. The droplet emittance is a function of three quantities:<sup>41</sup>

- (1) Absorptivity,  $\alpha$ , which is an intrinsic fluid property independent of geometry, and has units of  $\text{cm}^{-1}$
- (2) Droplet radius,  $R$
- (3) The reflectivity of the liquid surface,  $\rho_s$

Surface reflectivity is defined for the interface between a liquid (medium 2), and the adjacent medium 1, which is usually air. Surface reflectivity is wavelength dependent, and is given by  $\rho_s = 1 - (n_2/n_1)^2$ , where  $n$  is the index of refraction for the medium and wavelength of interest. Therefore, with a knowledge of  $n(\nu)$  and  $\alpha(\nu)$  for a working fluid of interest, radiative performance of a sheet of semi-transparent droplets can be predicted from the analytical results discussed in this section.

Experimental verification of the analytical predictions in this section is being carried out at NASA Lewis. A droplet sheet with a high width to thickness ratio characteristic of an operational LDR is being examined. Up to 2000 droplet streams of DC-705 are heated up to 400 K, and are projected through a 3.1 m test section, radiating in a  $10^{-4}$  torr vacuum to a simulated space environment at  $\sim 80$  K. The droplet sheet is 20 cm wide, 2 cm thick, and 3.1 m long. Details of the experimental apparatus are given elsewhere.<sup>17</sup>

#### Droplet Sheet Physics

In addition to radiative performance, an LDR droplet sheet must meet other requirements. Many issues related to desired performance depend solely on identification of the proper working fluid, and are discussed in the next section. Minimizing spacecraft contamination from the LDR implies proper generator and collector performance. The droplet sheet also must not be a source of possible contamination.

Droplet collisions, especially for a focused sheet of a triangular LDR, must be understood. Collisions within a stream are minimized or eliminated when droplet dispersions are sufficiently low. At present, intra-stream collisions are not the major concern, since droplet streams can travel up to 100 m without significant collisions.<sup>16,21</sup> Further investigation of this phenomenon for an LDR droplet generator is in progress.<sup>23</sup> The major source of collisions is from intersecting droplet streams. For orifices

spaced 2 mm apart, droplet streams from adjacent orifices can collide within 1 m. This assumes a trajectory accuracy of 1 mrad, which is the best accuracy demonstrated to date in the Ink Jet Printer industry. A trajectory accuracy of 10  $\mu$ rad, not yet demonstrated, would be needed to eliminate all collisions in a rectangular droplet sheet 100 m long. Collisions in a triangular droplet sheet cannot be avoided. Proper sheet design thus must consider the decrease in droplet flux with path length, and the corresponding increase in droplet diameter. Thus, with the number of droplet collisions known, the droplet sheet can be sized to radiate sufficient heat to space.

Two preliminary analyses<sup>5,12</sup> of droplet collisions conclude that a high degree of focusing is undesirable. For a triangular LDR, a small sheet width to length ratio is preferred. This will assure small angles of incidence and low impact velocities between colliding droplet streams. More detailed analysis is currently being conducted at both USC and MDAC. Results to date indicate that for the relative impact velocities expected in an LDR, droplet coalescence is predicted. Maximum impact velocities are 2 to 5 m/s for worst case conditions. Experimental verification of these results is in progress at USC.

Droplet collisions have been observed rather extensively at NASA Lewis. During in-house inspection of orifice plate trajectory, plates of poor quality were occasionally produced. Arrays of 10 droplet streams issuing from the plates were examined in a 10  $\mu$ m Hg vacuum. At low jet velocities, film effects caused significant misdirection of the droplet streams being examined. In many instances, droplet streams would collide, resulting in a new array of eight or nine jets, with one stream of droplets being 26 percent larger in diameter than before. This observation was made hundreds of times, and was often captured on 35 mm film. Angles of incidence were in the range of 1 to 30 mrad, which implied relative impact velocities up to 1.5 m/s. In all instances, droplet collisions resulted in coalescence. No scattering of secondary droplets was observed, even under lighting conditions where 10  $\mu$ m satellite droplets (limit of resolution) were detectable. These results indicate that, at least for low surface tension fluids such as DC-704, droplet collisions will always result in coalescence for low impact velocities. Higher impact velocities would be expected only in a highly focused droplet sheet.

Charging of droplets in the space plasma represents a possible loss mechanism. The effects of charging were considered in detail for altitudes above 150 km.<sup>5</sup> The worst deflection noted was in the plasma sheet, and fractional deflections less than 1  $\mu$ rad were calculated for all altitudes. Since orifice aiming accuracies are of the order of 1 mrad, this is insignificant. Currently, several investigators at JPL are experimentally simulating the effects of plasma charging on droplet trajectory. This will serve as verification of the analytical calculations.<sup>5</sup> A second mechanism of droplet charging occurs at droplet formation. Potentials up to 10 000 V have been observed on spacecraft surfaces. If the droplets become charged during formation,

subsequent deflection and repulsion could occur. To date, the magnitude of this effect has not been assessed. If this is identified as a critical issue, several proposed solutions could be investigated.

Atmospheric drag on an LDR droplet sheet is potentially a mechanism by which the working fluid could contaminate the spacecraft. A "worst case" geometry, where relative wind is normal to the direction of droplet travel, was assumed<sup>5</sup> in assessing the effects of atmospheric drag. An acceptable safety margin requires that the LDR be limited to missions above 250 to 300 km. If the LDR is constrained to an orientation where the relative wind is parallel to the droplet travel, no restriction on orbit altitude would apply. However, this deployment restriction could be unacceptable to some mission planners. Use of a drag shield to overcome the effects of atmospheric drag in LEO was briefly investigated,<sup>5</sup> but was judged to be relatively ineffective at the lower altitude orbits of interest.

One of the major advantages of the LDR over existing technology is its relative immunity to micrometeoroid damage. The modularized droplet generator of Fig. 6 is inherently immune to single point failure. Similarly, a linear collector for a rectangular LDR could be designed on an analogous basis. Thus, only a fluid return pipe for a single pass LDR requires fail-safe micrometeoroid protection; dual LDR's such as shown in Fig. 10 do not possess lengthy, massive fluid return lines. A cumulative flux distribution was assumed, and it was determined that a negligible fraction of the droplet sheet mass was lost per year due to droplet deflection by impacting micrometeoroids.<sup>8</sup> Similarly, a negligible fraction of the droplet mass is lost per year by droplet vaporization resulting from micrometeoroid impacts. The advantages of dividing a large radiator into trillions of microradiators is clearly demonstrated.

#### Working Fluid Selection

Stringent requirements are demanded of an LDR working fluid. A suitable liquid must have a low vapor pressure and must be chemically stable in the space environment of interest. A suitable liquid ideally has a low viscosity, high emissivity, low absorptivity to incident solar radiation, high surface tension, low density, high heat capacity and high thermal conductivity.<sup>17</sup> The working fluid must also be compatible with available generator and collector materials.

A number of liquid metals and Dow Corning 705 diffusion pump oil have been identified as candidate liquids.<sup>4</sup> It was observed that no suitable fluids existed for the 320 to 450 K range, which is of interest for some Brayton cycles. Two new alternatives were thus synthesized by Dow Corning, and relevant optical and physical properties of these experimental organosiloxanes were measured.<sup>42</sup> Vapor pressure characteristics for these and other candidate fluids are shown in Fig. 14. A literature search for low vapor pressure organic fluids did not reveal any new alternatives.<sup>15</sup> Inorganic salts have very low vapor pressures near their melting point. Because of concerns about materials compatibility, these are not considered promising.

Various eutectic compositions of liquid metals have been investigated.<sup>29</sup> These eutectics generally have unknown emissivities, but these have been estimated. When available, a pure metal is preferred over a eutectic composition, since a eutectic working fluid creates additional control problems. If the working fluid does not have precisely the same composition as the eutectic, differential evaporation (distillation) of the mixture can lead to a change in physical properties with time or temperature cycling. Surface oxidation in the atomic oxygen environment may also lead to differential evaporation of the eutectic liquid droplet. Such problems can be surmounted, but they introduce added complexity.

It has been suggested that working fluids be altered to improve their optical properties. For 200  $\mu\text{m}$  droplets of DC-704, droplet emittance is 0.17,<sup>41</sup> typical of liquid metals. Radiation from oil droplets is volumetric in nature. Droplet emittance can be increased significantly by increasing droplet radius. It could also be increased by addition of a suitable dye, if a chemically compatible dye could be identified for the oil of interest. For low emissivity liquid metals, adding a high emissivity powder (such as carbon black) to the liquid metal has been proposed.<sup>7</sup> This would be effective if the fine powder were dispersed on the metal surface, which appears likely. Investigators at USC are presently studying droplet formation in slurry streams. Other researchers have successfully formed droplet streams of a coal in water slurry.

An active effort is in progress to determine working fluid compatibility in orbital environments of interest. Since demonstration of a prototype LDR in orbit will be with a low temperature fluid, candidate oils have been considered first. Seven candidate oils were exposed to an atomic oxygen environment created by a plasma asher.<sup>43</sup> They included three siloxane fluids, namely DC-705, polymethylphenylsiloxane (PMPS), and polydimethylsiloxane (PDMS); and four perfluorinated polyethers, namely, Fomblin Z25, Krytox 143AB, Krytox 1502, and Krytox 16256. The perfluoroethers were found to be least affected by the atomic O conditions. However, even they showed a very slight degradation in the O environment, with the C-O ether bond being the most likely point of attack. Work is in progress to expose the candidate perfluoroethers to an atomic oxygen environment of 4.5 eV atoms. This is being carried out at both JPL and NASA Lewis to more fully understand the kinetics of the degradation reactions at the appropriate atomic O fluxes.

The preliminary results discussed above indicate that several different fluids may be required for a given temperature, depending on the mission environment and requirements. The siloxane fluids tested may not be suitable in the atomic O environment of LEO, but this needs further investigation. Owing to their superior vapor pressure and viscosity characteristics, siloxane fluids such as PDMS or PMPS may be suited for missions at higher altitudes, where atomic O fluxes are lower and vapor pressure requirements are more severe. It is generally agreed that fluorinated oils are more stable to atomic oxygen degradation than siloxane fluids. Since no Krytox or Fomblin fluids with suitable vapor pressure and viscosity characteristics are commercially available, NASA

Lewis is working informally with DuPont to synthesize new fluids chemically similar to Krytox.

Less is known about the stability of liquid metals such as Li, Ga, or Sn in the atomic oxygen environment. Metals readily form oxides with O, which in cases like  $\text{Al}_2\text{O}_3$  protect the metal from further attack. For a droplet flight time of perhaps 4 sec, kinetic studies of the oxide formation reactions at the appropriate atomic O fluxes are necessary. An oxide layer may not form during a short duration exposure. Formation of a metal oxide skin on the surface of a liquid metal droplet may actually be advantageous, since the droplet emissivity would be improved. A minor variation on a liquid metal LDR that would exploit the advantages of oxide formation has been suggested by JPL investigators. Kinetic studies of the reversible oxide formation reaction are required to assess the feasibility of a metal/metal oxide working fluid.

A suitable working fluid must also be resistant to degradation from radiation and from other constituents of the space plasma. Siloxane fluids are polymerized after exposure to uV, resulting in significant changes in viscosity. Radiation effects, particularly from uV and vacuum uV radiation, are currently being investigated at JPL for candidate low temperature LDR fluids. Synergistic effects from combined exposure to atomic O and uV have been identified for certain materials.

Optical properties of candidate working fluids must be accurately known, since errors in property estimation have a tremendous impact on system design. Emissivity measurements for candidate liquid metals are complicated by oxide formation on a newly created surface. For semi-transparent oils, all required optical properties can be determined from a knowledge of absorptivity,  $\alpha(\nu)$ , and refractive index,  $n(\nu)$ .<sup>41</sup> Absorptivity is usually approximated from transmission measurements at two or more film thicknesses. Significant experimental errors are often associated with this method, for a number of esoteric reasons. Much more accurate measurements can be made with a total reflectance approach.<sup>44</sup> An experimental spectrum is obtained, and  $n(\nu)$  and  $\alpha(\nu)$  are obtained through an iterative procedure, using a Kramers-Kronig transformation. Work is in progress at NASA Lewis to apply this method to candidate LDR fluids.

#### Control of Spacecraft Contamination

A significant critical issue in developing an LDR is to minimize or eliminate spacecraft contamination from the LDR. At least five sources of contamination have been identified. Working fluid lost by any one of these five mechanisms can be transported to the spacecraft in at least six ways. Any evaporated fluid can recondense on the spacecraft. Backscattering of the evaporated working fluid by the space plasma can occur. Liquid can also creep along the LDR structure to reach the spacecraft proper. Charged liquid droplets can also be attracted to a spacecraft which has developed a charge opposite to that of the droplet. Droplets which impact a spacecraft surface can release secondary contaminants. Finally, splashed droplets can travel directly from the LDR to the spacecraft.

Perhaps the most recognized source of contamination is from splashed droplets. Droplet collisions, especially in a focused sheet, can generate secondary satellite droplets if the relative impact velocity is high. As discussed earlier in this paper, droplet collisions appear to be inconsequential, since coalescence occurs. Splashed droplets can also be released at the collector. To keep collector mass loss insignificant, a design goal of one in  $10^8$  has been assumed. A more efficient collector would primarily minimize contamination concerns. The design goal has been demonstrated for a linear collector,<sup>12</sup> and is in the process of being demonstrated for a rotating collector.

Misdirected droplet streams are also a perceived concern. The droplet generator of Fig. 6 eliminates this fear, since an individual module can be turned off if a misdirected stream is noted. Orifice arrays will need to be flight qualified after fabrication. The only cause of misdirected droplet streams would be from a micrometeoroid impacting and damaging an orifice array. Here again, generator modularization minimizes this concern.

A liquid film can also migrate from the generator or collector along the LDR structure to the spacecraft. The shear seal design proposed by Grumman, and discussed earlier, would eliminate fluid films at the generator, if the feasibility of the concept can be demonstrated. Nonwetting coatings applied to the appropriate surfaces of the droplet generator and collector are a potential solution. This is being examined in the current development of the centrifugal collector. The liquid films developed at the droplet generator have been observed experimentally only at module startup or shutdown. Liquid films at the collector are apparently possible during steady state operation. However, the rotating shroud collector is designed to minimize or eliminate such films.

A potentially significant source of contamination is from evaporation of the working fluid. Some investigators have assumed a vapor pressure requirement of  $10^{-7}$  torr.<sup>4</sup> This criterion was arrived at by calculating the vapor pressure that would result in an evaporative mass loss in 30 yr equal to the sheet mass. Molecules evaporating from one droplet can recondense upon contact with other droplets. The extent to which this can occur is not sufficiently understood. The desired vapor pressure to assure an insignificant evaporative loss is in the  $10^{-9}$  to  $10^{-7}$  torr range. Arriving at a vapor pressure criterion to keep contamination from evaporating droplets at an acceptable level is more difficult. Critical optical surfaces may be adversely affected by the presence of a monolayer of contaminant. For other missions, contamination requirements will not be as stringent. Thus, vapor pressure requirements may be more or less restrictive than  $10^{-9}$  torr, and can only be determined for a well defined mission and spacecraft-radiator orientation.

In addition to minimizing contamination through proper design of components and proper choice of working fluid, other solutions have been proposed. The use of baffles between the LDR and the spacecraft proper appears feasible,<sup>8</sup> since free molecular flow exists. A cold

plate can be located on the spacecraft to induce controlled condensation. Proper control of spacecraft potential will eliminate contamination from electrostatically attracted droplets. When a tethered power system is present, as in some nuclear powered missions, the LDR can be located far from the spacecraft, near the power system. For nontethered missions, contamination can be minimized merely by locating the LDR as far away from sensitive surfaces as possible. When droplet evaporation is most significant, the droplet generator should be placed as far as possible from sensitive areas. If droplet splashing is the predominant source of fluid loss, the collector should be located as far from optical surfaces as possible.

If the approaches outlined above are not considered satisfactory, the entire LDR can be enclosed by a plastic film of micron thickness.<sup>8</sup> Such a film would be required to transmit radiation in the 2 to 20  $\mu\text{m}$  range. The film would be of negligible mass.

The merits of an enclosed LDR over an exposed fluid LDR have not been appreciated. Spacecraft users and mission planners are generally uncomfortable with exposed fluid radiators. Enclosing the droplet sheet, generator, and collector does not present any significant technical challenges, assuming a suitable material is identified. The advantages are enormous. It is recognized that micrometeoroids will puncture the film many times over the radiator lifetime. The effects of such exposure have been calculated<sup>45</sup> in detail for a 10 yr radiator lifetime. Despite repeated punctures by micrometeoroids, the film would fulfill its intended function. Vapor pressure requirements can be relaxed to  $10^{-6}$  torr,<sup>45</sup> since contamination is no longer a concern. Atmospheric drag on the droplet sheet would be reduced, thus removing constraints on LDR orientation for 250 km orbits. Atomic oxygen fluxes inside the film would be lower than ambient values. Some film materials would reduce the intensity of UV radiation on the droplets. Thus, working fluid compatibility requirements could prove easier to achieve.

In conclusion, contamination concerns for an LDR have generally been addressed by attempting to eliminate the sources of contamination. Droplet splashing at collector impact has not been quantified, although the collector is being designed to capture a large fraction of rebounded droplets. Low temperature working fluids with vapor pressures of  $10^{-10}$  torr have been developed, and thus evaporation rates are quite low. Liquid metals of interest, notably gallium, can have even lower vapor pressures. An enclosed LDR may only be necessary to alleviate user concerns, as contamination may not be significant. For many missions, enclosing the LDR in a transparent film is probably not necessary. Precise conclusions cannot be made, since contamination requirements for future missions have not been defined.

#### Microgravity Testing

Development of an LDR requires a demonstration of generator, collector, and droplet sheet performance in microgravity. Proper design of the droplet generator requires an assessment of transient operation in microgravity. Of particular

interest are the effects of a fluid film on jet formation, and subsequent break up of the jet into uniform droplets. To this end, testing is currently being conducted at the NASA Lewis Zero Gravity Facility, which allows 5.2 sec of  $10^{-5}$  g testing. The experimental apparatus is described elsewhere,<sup>17</sup> and allows activity at the droplet generator to be filmed at 400 frames/sec. Only preliminary conclusions can be drawn from the testing to date. The desired jet formation has been demonstrated for two important conditions. In one series of tests, the exit side of the generator was not wet by the liquid before jet startup. This condition is the preferred mode of generator operation. In another series of tests, the jet broke through a 6 mm thick pool of liquid after flowing through the orifice. In both cases, the jets immediately achieved the desired trajectory, with no misdirection at the instant of startup. Orifice diameters investigated to date are 85, 135, and 200  $\mu\text{m}$ . Testing with a thin film (maybe 500  $\mu\text{m}$  to 1 mm thick) present before startup is in progress. Of particular importance will be future tests with 10-orifice arrays. These tests will closely simulate the startup of a droplet generator in orbit.

Development of a centrifugal collector, currently being carried out by MDAC, Spectra Technology, and Spectron Development Labs, will require zero gravity demonstration. This is currently planned for March 1988. Future testing of a sub-scale LDR prototype is being planned as part of the Technology Development and Mission Experiments (TDMX) program. To this end, NASA Lewis and NASA Johnson personnel are working to define requirements.

#### Mission and System Analysis

A meaningful comparison of the LDR with alternative radiator concepts requires an accurate estimation of LDR system mass. Early system studies<sup>4,22,39</sup> are misleading, since system mass estimates are grossly in error. The first good estimate of system mass<sup>5</sup> was based on reliable mass estimates for the generator, collector, working fluid, structure, return pipes, and pumps. Subsequent system mass calculations<sup>6,17</sup> have improved on the initial assumptions. More refined system studies are contingent on the specific designs for the droplet generator and collector. A large portion of the droplet generator mass is that of the working fluid.<sup>5,22</sup> A focus in current generator design<sup>23</sup> is to reduce its mass, and to accurately estimate the mass of the improved design. A preliminary estimate of structural mass<sup>5,46</sup> considers the frequencies and vibrational modes which must be avoided in designing the truss structure. Similar considerations have been made in estimating generator and collector mass.<sup>5</sup> Details of the system mass estimates will not be discussed here.

Proper design of a total LDR system requires a parametric investigation of key issues. Droplet sheet geometry for a given heat rejection load must be determined before generator and collector designs can be finalized. If droplets spacing is greater than 10 diameters, the droplet sheet behaves essentially as isolated droplets, with very little occlusion of radiation.<sup>41</sup> Such an optically thin sheet is highly efficient, but is associated with a massive generator and

collector. An optically dense sheet (high  $\tau$ ) is less efficient, but component masses and sheet area are lower. For a given working fluid with droplet emittance,  $\epsilon_0$ , choosing  $\tau = 0.5\epsilon_0$  was determined to be an optimum choice between a low mass LDR and a minimum area design.<sup>40</sup> Further insight into the optimum sheet geometry considers the incremental increase in sheet emittance with additional droplet layers,<sup>12,37</sup> as shown in Fig. 13.

Proper choice of droplet velocity, diameter, and working fluid was examined in an LDR systems study at MDAC.<sup>6</sup> Because of several questionable estimates of system mass, some of the conclusions are quantitatively in error. Nevertheless, the findings are significant, since qualitative conclusions can be drawn. The effects of velocity were studied for 1 and 10 MW LDR's. Lower velocities were preferred at 1 MW, and higher velocities at 10 MW. This was found to depend on the relative contributions of the collector and the supporting structure to the total system mass for the 1 and 10 MW designs. Thus, no simple criterion on droplet velocity can be stated, since the choice will depend on mission requirements. The effects of droplet diameter are similar. For nonopaque oils, diameter has a significant effect on droplet emittance, whereas for metals, it does not. The effects of droplet diameter on LDR system mass have been studied for an LDR rejecting lithium droplets at 510 K.<sup>46</sup> For this LDR point design, smaller droplets significantly decreased LDR system mass. System mass was found to be quite sensitive to fluid density, fluid specific heat, and emissivity. System mass is a weak function of radiator orientation (with respect to the sun, earth, and spacecraft).<sup>6</sup>

The optimum ratio of sheet width to length is highly dependent on power levels and mission requirements, especially for a triangular LDR. As discussed earlier, choice of this ratio depends on the behavior of colliding droplets. If coalescence of droplets colliding at high impact velocities ( $\sim 5$  m/s) does not occur, the width/length ratio must be chosen to eliminate droplet splashing in a highly focused droplet sheet. Droplet velocity also has a significant impact on the aspect ratio. A proper choice of aspect ratio depends on many factors, and has apparently not been investigated in detail.

With LDR system mass known, potential missions enhanced or enabled by an LDR can be evaluated. A knowledge of power system mass and operation is required. For dynamic power systems, it is sometimes necessary to re-optimize the cycle for an LDR.<sup>17</sup> Radiator mass is a dominant percentage of power system mass<sup>47</sup> at multi-megawatt levels. A lower heat rejection temperature improves cycle efficiency but also increases radiator mass. Significantly lower LDR specific mass, as compared to existing technology, requires a re-optimization of the power cycle. A lower heat rejection temperature may minimize the need for recuperated dynamic cycles, thus lowering their mass. A proper comparison of radiator concepts must consider these facts.

Many types of missions which would potentially benefit from an LDR have been investigated.<sup>5,6,17</sup> NASA and DOD missions requiring burst power, the storage of cryogenic fuels, and

high maneuverability are examples. The relative ease with which an LDR can be deployed, as illustrated in Fig. 2, allows high maneuverability missions to be considered. An LDR would not be applicable for missions requiring continuous heat rejection during maneuvering. Missions where rapid attitude adjustments are required benefit from an LDR, if a short-term thermal storage system is included. Multi-megawatt missions require large radiator areas. For conventional technology, a 1000 m<sup>2</sup> radiator limits maneuverability. This is no longer a concern for an LDR which can be quickly reduced in area. For certain DOD missions, a large area conventional radiator would be an inviting target for hostile threats; the LDR droplet sheet, which represents the majority of LDR area, may be less susceptible to such threats.<sup>5,6</sup> Manned space platforms, laser and particle beam vehicles, growth versions of Space Station, certain SP-100 missions, and space based radar are all potentially enhanced by an LDR. An OTV using a nuclear Brayton cycle with an LDR to generate 10 MW of electrical power has been studied,<sup>48</sup> and the advantages of an LDR were clearly demonstrated.

Since the radiator is such a dominant percentage of power system mass for large power systems,<sup>47</sup> extensive investigation of LDR usage in megawatt and kilowatt missions has been conducted. Figure 15<sup>46</sup> shows the power levels at which certain LDR working fluids are most advantageous. Radiator specific power for aluminum, tin, and lithium LDR's is maximized around 5 MW. For lower temperature heat rejection, an LDR using NaK as a working fluid is preferred at the 200 kW power level. Direct comparisons of LDR and heat pipe technology are shown in Figs. 16 and 17. Figure 16 indicates the radiator specific power for candidate LDR working fluids.<sup>46</sup> For comparison, heat pipe technology assuming a 5 kg/m<sup>2</sup> specific mass and a surface emissivity of 0.85 is also shown. If droplet emittance of the liquid metals can be improved with a high emissivity additive distributed on the droplet surface, LDR performance is even more impressive. The parallel LDR configuration of Fig. 10 eliminates the mass of fluid return lines, and minimizes structural mass. If this arrangement is employed, the LDR specific powers of Fig. 16 are even higher. Lithium, NaK, and Dow Corning 705 LDR's can be seen to be 5 to 10 times lighter than heat pipe radiators. The effect of power cycle temperature ratio on the mass of a 100 kW<sub>e</sub> nuclear Stirling power system<sup>17</sup> can be seen in Fig. 17. An LDR is preferred when the droplet sheet emittance is greater than 0.3, which is easily achieved at realistic sheet optical thicknesses. The Stirling cycle hot end temperature in this case is 1050 K, implying the use of lithium or a eutectic to be compatible with rejection temperatures of 450 to 600 K.

#### Conclusions and Future Efforts

Development of an LDR is proceeding. To date, no unresolvable technical issues have been identified. Rectangular and triangular geometries appear to be the most promising of all the LDR configurations proposed to date. Operation of the linear collector has been demonstrated in simulated microgravity testing, but a further demonstration of collector pumping is required. If successful operation of a centrifugal collector

can be demonstrated, the triangular (focused) LDR will be the preferred configuration.

A conceptual design of a liquid droplet generator, applicable for either a focused or unfocused sheet, has been presented. The design considers the constraints on droplet formation that have been observed experimentally. Orifice fabrication limitations that have been identified are considered in determining the degree to which the generator should be segmented. Modularization of the generator allows it to be resistant to single point failure resulting from micrometeoroid encounters or other failure modes.

Proper sizing and geometry of the droplet sheet have been considered in detail. The heat radiated from the rectangular sheet has been analyzed in detail. Analytical predictions for a cylindrical droplet cloud were found to be in very good agreement with experimental observations. Radiative behavior of a focused droplet sheet has not been analyzed in as much detail, and is less well understood. The droplet sheet is found to be relatively immune to micrometeoroid showers and hostile threats. However, atmospheric drag on a droplet sheet may limit the LDR to missions above 250 km. Droplet charging in the space plasma is shown to be inconsequential. Similarly, droplet collisions, especially in a focused sheet, will result in coalescence rather than splashing if the LDR is properly designed.

A number of candidate LDR working fluids covering the 270 to 1000 K range have been identified. Long term stability of candidate fluids in orbital environments of interest is still under investigation. Certain fluids appear to be restricted to certain types of missions, but more research is required. Working fluids must be properly chosen to minimize possible spacecraft contamination from evaporating droplets. Without well-defined mission requirements, it is impossible to quantify vapor pressure requirements necessary to address this concern.

Other mechanisms by which an LDR could potentially contaminate a spacecraft have been identified. Proper LDR system design minimizes these concerns. The use of an enclosed LDR will further alleviate user concerns about possible spacecraft contamination.

For a wide range of missions, LDR's are found to be advantageous when compared to heat pipe radiators. Comparison of the LDR with other proposed advanced radiators is discussed elsewhere.<sup>9,25,45,49</sup> Total LDR mass is often 5 to 10 times less than for 5 kg/m<sup>2</sup> heat pipe technology, especially for megawatt rejection levels. A much lighter radiator requires that power cycles be reoptimized, since the radiator mass penalty at lower power cycle rejection temperatures is less significant with an LDR.

In LDR development to date, the relevant technology issues have been identified and analyzed. A number of issues have been resolved, with unresolved issues being actively investigated. It is necessary to accurately assess the spray quality afforded by current NASA Lewis fabrication technology. The behavior of the droplet generator at startup and shutdown in microgravity must be further investigated. A centrifugal

collector must be demonstrated in both earth and zero gravity environments. More detailed generator and collector designs will allow more accurate LDR system mass estimates to be made. Promising working fluids identified to date must be further investigated for long term chemical stability. To date, no critical technology issues without a plausible solution have been identified.

Given current funding and manpower limitations, it appears that the issues discussed above will be sufficiently resolved by the end of 1988. A demonstration of a pre-prototype LDR would then be planned, assuming that no insoluble critical issues are discovered before then. NASA Lewis is currently participating in the TDMX Program to develop plans for demonstration of a pre-prototype LDR, using either STS or the Space Station as the experimental test bed. Several nongovernment organizations have developed and submitted similar proposals.

### References

1. Calia, V., Haslett, R., Konopka, W., and Kosson, R., "Liquid Droplet Radiator Collector Development," Advanced Energy Systems - Their Role in our Future, Vol. 1, American Nuclear Society, La Grange Park, IL, 1984, pp. 216-223.
2. Teagan, W.P. and Fitzgerald, K.F., "Liquid Belt Radiator Design Study," NASA CR-174901, 1986.
3. Hedgepeth, J.M. and Knapp, K., "Preliminary Investigation of a Dust Radiator for Space Power Systems," Astro Research Corporation, ARC-TN-1054, Mar. 1978.
4. Mattick, A.T. and Hertzberg, A., "Liquid Droplet Radiators for Heat Rejection in Space," Energy to the 21st Century, Vol. 1, AIAA, New York, 1980, pp. 143-150.
5. Mattick, A.T. and Taussig, R.T., "New Thermal Management and Heat Rejection Systems for Space Applications," AFRPL TR-84-039, 1984.
6. Mankamy, M.M., Snyder, R.E., and Taussig, R.T., "Liquid Droplet Radiator Systems Investigation," AFRPL TR-85-080, 1985.
7. Mattick, A.T. and Hertzberg, A., "Liquid Droplet Radiators for Heat Rejection in Space," Journal of Energy, Vol. 5, No. 6, Nov.-Dec. 1981, pp. 387-393.
8. Mattick, A.T. and Hertzberg, A., "The Liquid Droplet Radiator -- An Ultralightweight Heat Rejection System for Efficient Energy Conversion in Space," Acta Astronautica, Vol. 9, No. 3, Mar. 1982, pp. 165-172.
9. Prenger, F.C. and Sullivan, J.A., "Conceptual Designs for 100-MW Space Radiators," LA-UR-82-3279, 1982.
10. Botts, T.E., Powell, J.R., and Horn, F.L., "Magnetic Focusing of Liquid Droplet Sheets for Heat Rejection in Space," AFRPL TR-83-072, 1983.
11. Botts, T.E., Powell, J.R., and Horn, F.L., "Magnetic Droplet Radiator Collectors," Space Nuclear Power Systems 1984, Vol. 2, M. S. El-Genk and M.D. Hoover, eds., Orbit Book Company, Malabar, FL, 1985, pp. 437-445.
12. "Liquid Droplet Radiator Collector Component Development," AFRPL TR-85-082, 1985.
13. Sweet, R.G., "High-Frequency Oscillography with Electrostatically Deflected Ink Jets," Stanford Electronic Laboratories, SEL-64-004, Mar. 1964.
14. Orme, M. and Muntz, E.P., "New Technique for Producing Highly Uniform Droplet Streams Over an Extended Range of Disturbance Wavenumbers," Review of Scientific Instruments, Vol. 58, No. 2, Feb. 1987, pp. 279-284.
15. King, R., "Experimental Studies of the Liquid Droplet Radiator," M.S. Thesis, University of Washington, 1983.
16. Dixon, M.A., "Study of the Formation and Propagation of Ultra-Coherent Droplet Streams in a Vacuum," M.S. Thesis, University of Southern California, 1985.
17. Presler, A.F., Coles, C.E., Diem-Kirsop, P.S., and White, K.A. III, "Liquid Droplet Radiator Program at the NASA Lewis Research Center," NASA TM-87139, 1986. (Also, ASME Paper 86-HT-15, June 1986.)
18. Leib, S.J. and Goldstein, M.E., "The Generation of Capillary Instabilities on a Liquid Jet," Journal of Fluid Mechanics, Vol. 168, July 1986, pp. 479-500.
19. Leib, S.J. and Goldstein, M.E., "Convective and Absolute Instability of a Viscous Liquid Jet," Physics of Fluids, Vol. 29, No. 4, Apr. 1986, pp. 952-954.
20. Muntz, E.P. and Dixon, M., "The Characteristics, Control and Uses of Liquid Streams in Space," AIAA Paper 85-0305, Jan. 1985.
21. Muntz, E.P. and Dixon, M., "Applications to Space Operations of Free-Flying, Controlled Streams of Liquids," Journal of Spacecraft and Rockets, Vol. 23, No. 4, July-Aug. 1986, pp. 411-419.
22. Knapp, K., "Liquid Droplet Radiators for Heat Rejection in Space," ARC-TN-1113, June 1982.
23. Orme, M., et al., "The Design and Performance of a Multi-Stream Droplet Generator for the Liquid Droplet Radiator," AIAA Paper 87-1538, June 1987.
24. Chubb, D.L. and White, K.A., "Liquid Sheet Radiator," AIAA Paper 87-1525, June 1987.
25. Feig, J.R., "Radiator Concepts for High Power Systems in Space," Space Nuclear Power Systems 1984, Vol. 2, M.S. El-Genk and M.D. Hoover, eds., Orbit Book Company, Malabar, FL, 1985, pp. 483-490.



26. Brandell, B., Feig, J.R., Taussig, R.T., Matlock, R.S., and Francis, R., "Status of Liquid Droplet Radiator Systems Analysis Techniques," Advanced Energy Systems - Their Role in Our Future, Vol. 1, American Nuclear Society, La Grange Park, IL, 1984, pp. 139-145.
27. Mattick, A.T. and Nelson, M., "Heat Transfer Studies on the Liquid Droplet Radiator," Space Nuclear Power Systems 1985, Vol. 3, M.S. El-Genk and M.D. Hoover, eds., Orbit Book Company, Malabar, FL, 1986, pp. 113-118.
28. McFall, K., "A Theoretical Analysis of Radiative Heat Transfer Within a Planar Sheet of Spherical Droplets," M.S. Thesis, University of Washington, 1986.
29. Mattick, A.T. and Hertzberg, A., "Liquid Droplet Radiator Performance Studies," Acta Astronautica, Vol. 12, No. 7/8, July-Aug. 1985, pp. 591-598.
30. Siegel, R., "Transient Radiative Cooling of a Droplet-Filled Layer," Journal of Heat Transfer, Vol. 109, No. 1, Feb. 1987, pp. 159-164.
31. Siegel, R., "Separation of Variable Solution for Nonlinear Radiative Cooling," International Journal of Heat and Mass Transfer, to be published, Vol. 30, 1987.
32. Siegel, R., "Radiative Cooling of a Layer With Nonuniform Velocity -- A Separable Solution," Journal of Thermophysics and Heat Transfer, to be published, 1987.
33. Siegel, R., "Transient Radiative Cooling of a Layer Filled With Solidifying Drops," Journal of Heat Transfer, to be published, Vol. 109, 1987.
34. Nelson, M.J., "Measurement of the Heat Transfer of a Cloud of Oil Droplets," M.S. Thesis, University of Washington, 1985.
35. Simon, M.A., "Experimental Test of Liquid Droplet Radiator Performance," M. S. Thesis, University of Washington, 1985.
36. Mattick, A.T. and Simon, M.A., "Experimental Test of Liquid Droplet Radiator Performance," Presented at the 3rd Symposium on Space Nuclear Power Systems, Albuquerque, NM, Jan. 1986.
37. Brown, R.F. and Kosson, R., "Liquid Droplet Radiator Sheet Design Considerations," Advanced Energy Systems - Their Role in Our Future, Vol. 1, American Nuclear Society, La Grange Park, IL, 1984, pp. 330-338.
38. Brandell, B., "Analytical Approach and Computer Model Development for Performance Investigations of Liquid Droplet Radiators," SAE Paper 840977, July 1984.
39. Knapp, K., "A Parametric Study of Liquid-Droplet Stream Radiators," Astro Research Corporation, ARC-TN-1095, Dec. 1980.
40. Mattick, A.T. and Herzberg, A., "Liquid Droplet Radiator Technology Issues," Space Nuclear Power Systems 1984, M.S. El-Genk and M.D. Hoover, eds., Orbit Book Company, Malabar, FL, 1985, pp. 427-435.
41. Edgerton, R.H. and Diem-Kirsop, P.S., "Liquid Droplet Radiator Thermal Characteristics," Space Systems Technology Conference 1986, AIAA, NY, 1986, pp. 4-14. (Also, AIAA Paper 86-1162).
42. Buch, R.R. and Huntress, A.R., "Organosiloxane Working Fluids for the Liquid Droplet Radiator," NASA CR-175033, 1985.
43. Gulino, D.A. and Coles, C.E., "Effect of an Oxygen Plasma on the Physical and Chemical Properties of Several Fluids for the Liquid Droplet Radiator," AIAA Paper 87-0080, Jan. 1987. (Also, NASA TM-88839.)
44. Harrick, N.J., Internal Reflection Spectroscopy, Harrick Scientific Company, New York, 1967.
45. Elliott, D.G., "Rotary Radiators for Reduced Space Powerplant Temperatures," Space Nuclear Power Systems 1984, Vol. 2, M.S. El-Genk and M.D. Hoover, eds., Orbit Book Company, Malabar, FL, 1985, pp. 447-453.
46. Taussig, R.T. and Mattick, A.T., "Droplet Radiator Systems for Spacecraft Thermal Control," Journal of Spacecraft and Rockets, Vol. 23, No. 1, Jan. 1986, pp. 10-17.
47. Juhasz, A.J. and Jones, B.I., "Analysis of Closed Cycle Megawatt Class Space Power Systems With Nuclear Reactor Heat Sources," Presented at the 4th Symposium on Space Nuclear Power Systems, Albuquerque, NM, Jan. 1987.
48. Beals, G., Chin, J., Day, J., Gibson, C., Grevstad, K., Larson, G., and Treiber, D., "Light-Weight Nuclear-Powered OIV Utilizing a Liquid Droplet Radiator," AIAA Paper 83-1346, June 1983.
49. Koenig, D.R., "Rotating Film Radiators for Space Applications," Energy for the 21st Century, SAE P-164, Vol. 1, Society of Automotive Engineers, Warrendale, PA, 1985, pp. 1.439-1.445.

ORIGINAL PAGE IS  
OF POOR QUALITY

RADIATIVE "FINS" AND "HEAT PIPES" OF CONVENTIONAL RADIATORS  
REPLACED BY MULTIPLE STREAMS OF UNIFORM LIQUID DROPLETS

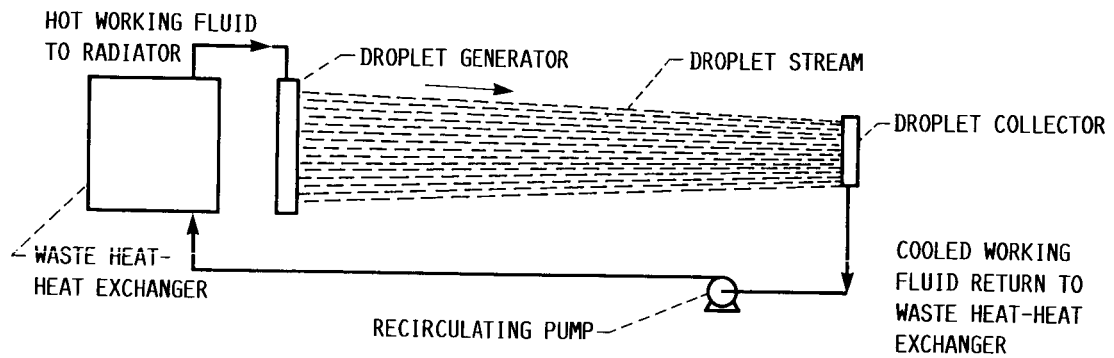


FIGURE 1. - LIQUID DROPLET RADIATOR CONCEPT.

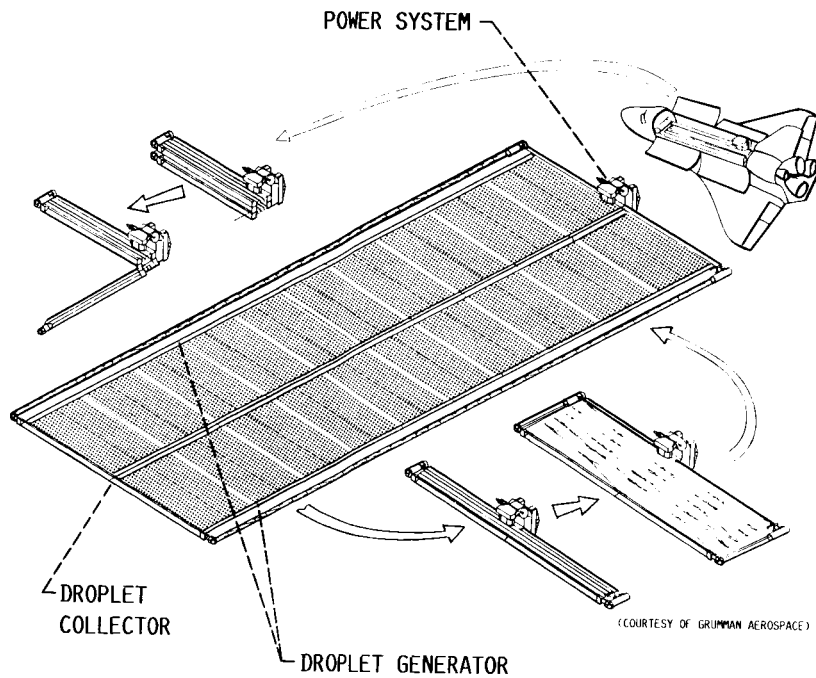


FIGURE 2. - DEPLOYMENT OF RECTANGULAR LDR.

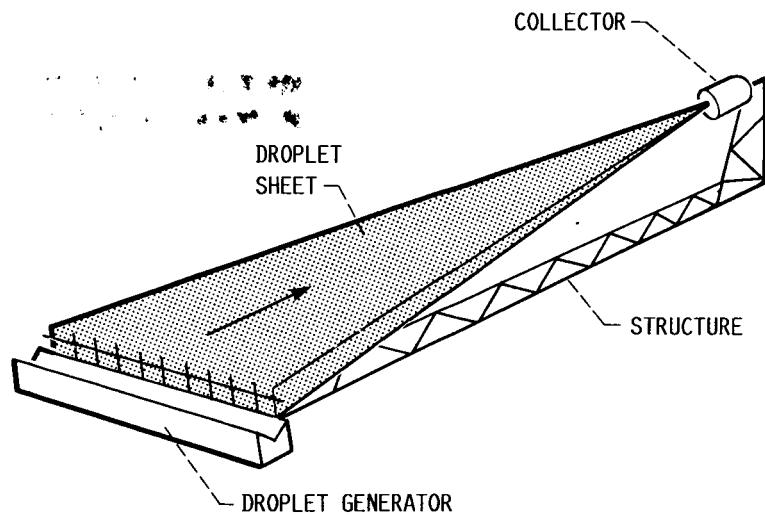


FIGURE 3. - TRIANGULAR LDR.

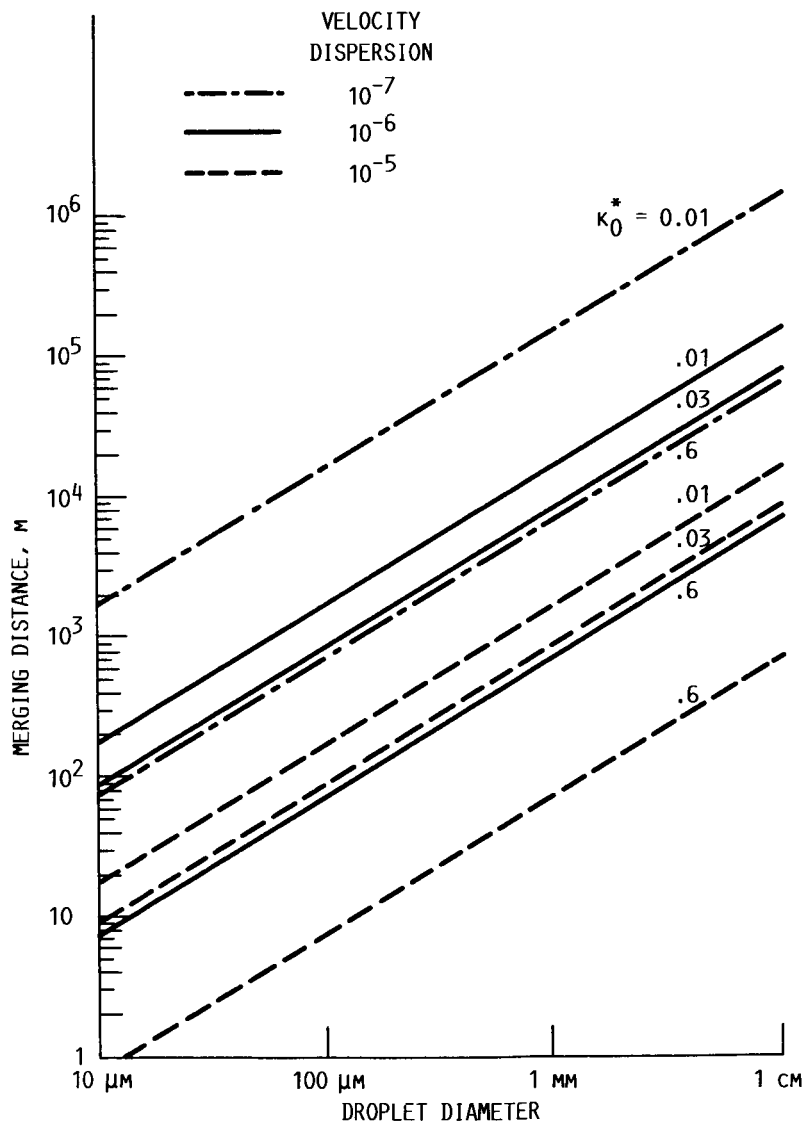


FIGURE 4. - DISTANCE A SINGLE DROPLET STREAM CAN TRAVEL WITHOUT SIGNIFICANT AGGLOMERATION, WITH NONDIMENSIONAL WAVENUMBER AND VELOCITY DISPERSION AS PARAMETERS.

ORIGINAL PAGE IS  
OF POOR QUALITY

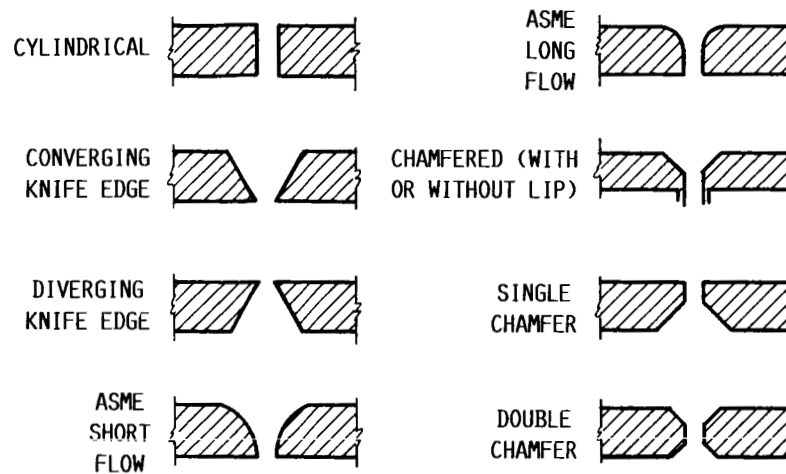
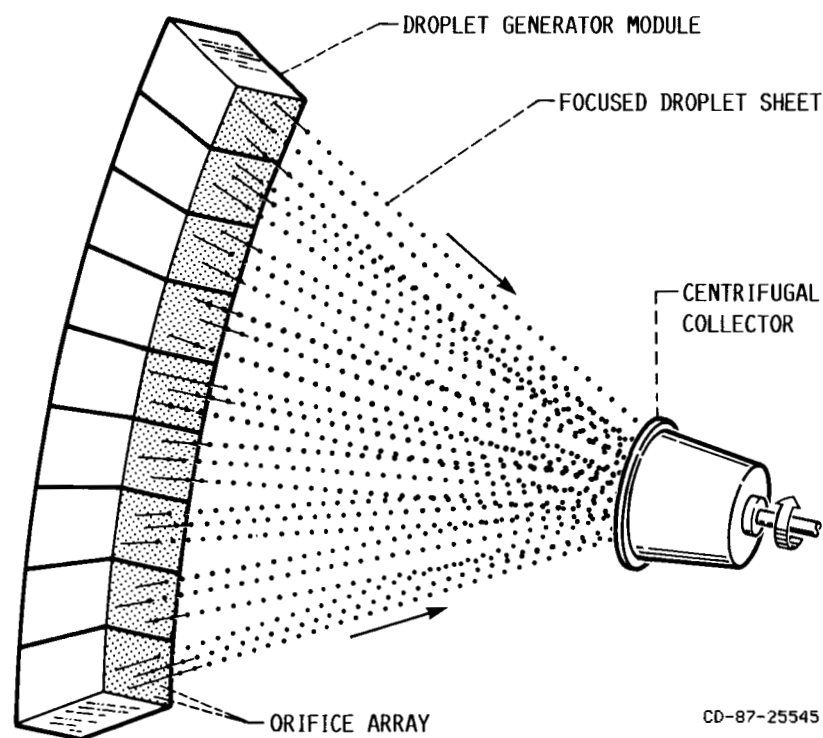


FIGURE 5. - EXPERIMENTAL ORIFICE GEOMETRIES.



CD-87-25545

FIGURE 6. - FOCUSED, MODULAR DROPLET GENERATOR.

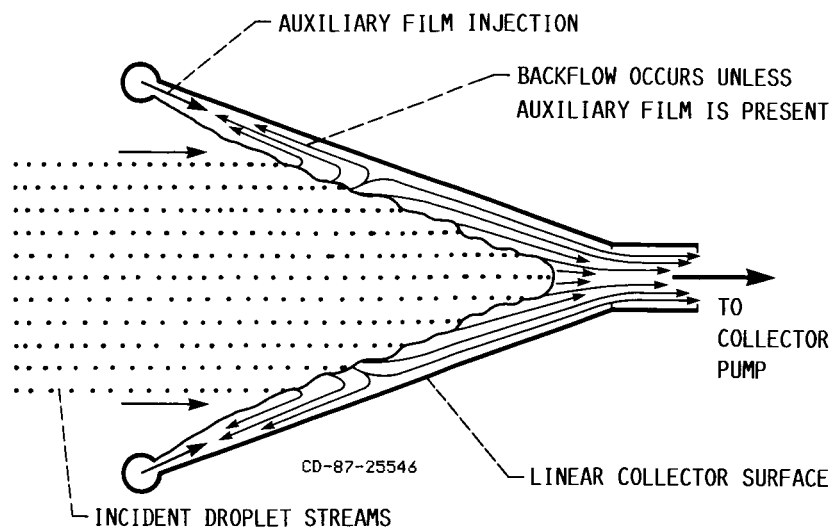


FIGURE 7. - LINEAR COLLECTOR SCHEMATIC, AND USE OF AUXILIARY FILM TO PREVENT BACKFLOW ON COLLECTOR SURFACE.

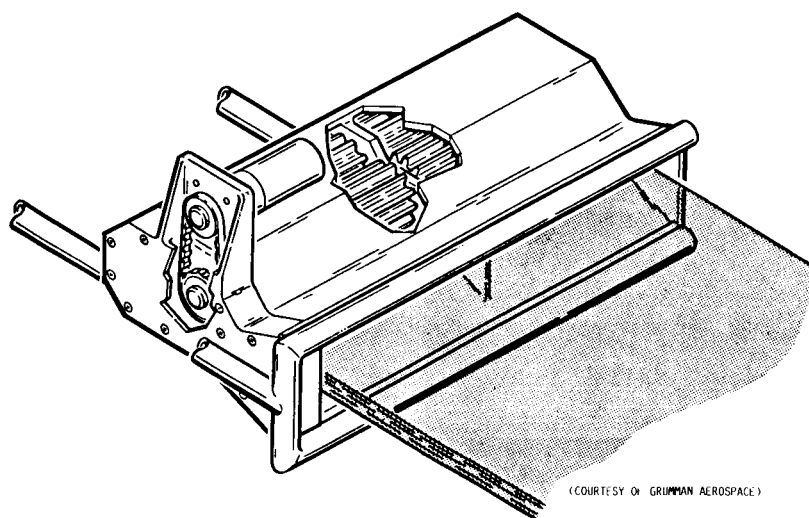
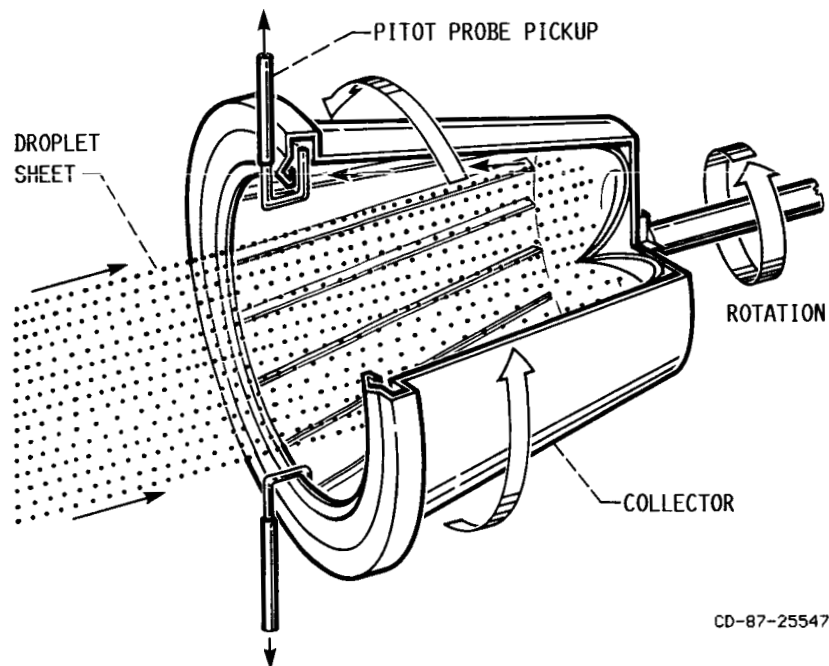


FIGURE 8. - ONE-SIDED LINEAR COLLECTOR AND GEAR PUMP.

ORIGINAL PAGE IS  
OF POOR QUALITY



CD-87-25547

FIGURE 9. - CENTRIFUGAL COLLECTOR WITH PITOT TUBE FLUID COLLECTION.

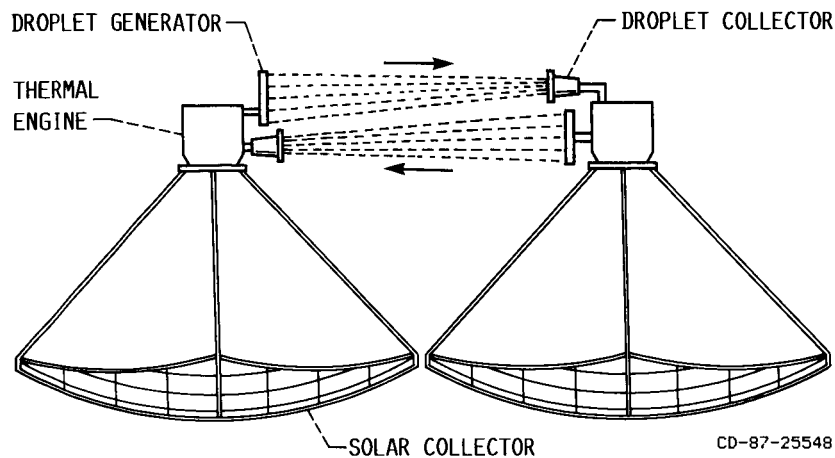


FIGURE 10. - USE OF PARALLEL LDR'S TO MINIMIZE MASS OF SUPPORTING STRUCTURE AND PIPING.

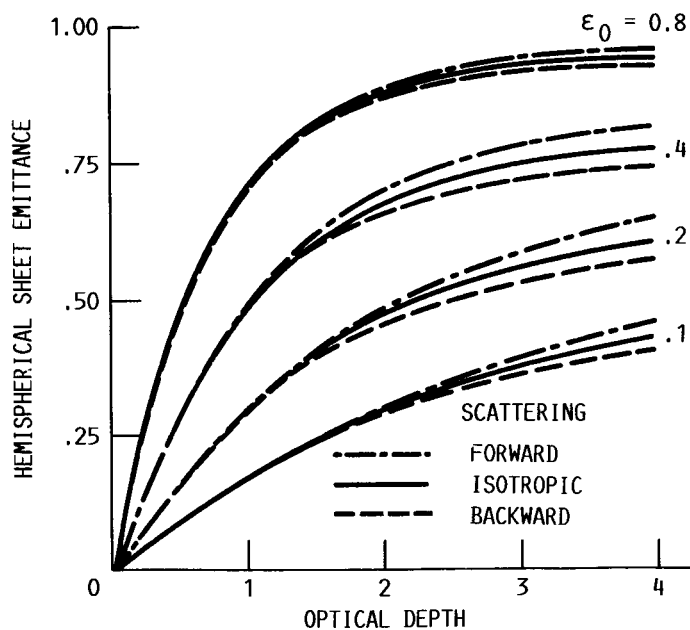


FIGURE 11. - DEPENDENCE OF SHEET EMITTANCE ON DROPLET SURFACE EMISSIVITY ( $\epsilon_0$ ), OPTICAL DEPTH AND METHOD OF DROPLET SCATTERING.

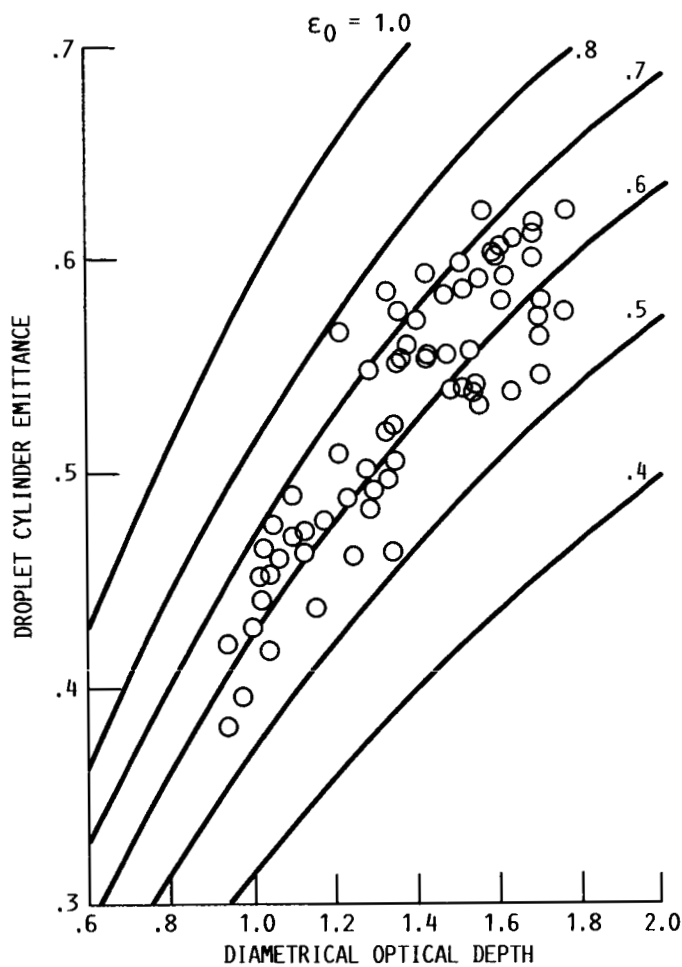


FIGURE 12. - EMITTANCE OF CYLINDRICAL CLOUD OF DROPLETS FOR SEVERAL VALUES OF DROPLET EMITTANCE ( $\epsilon_0$ ). COMPARISON OF EXPERIMENTAL RESULTS WITH THEORETICAL PREDICTIONS.

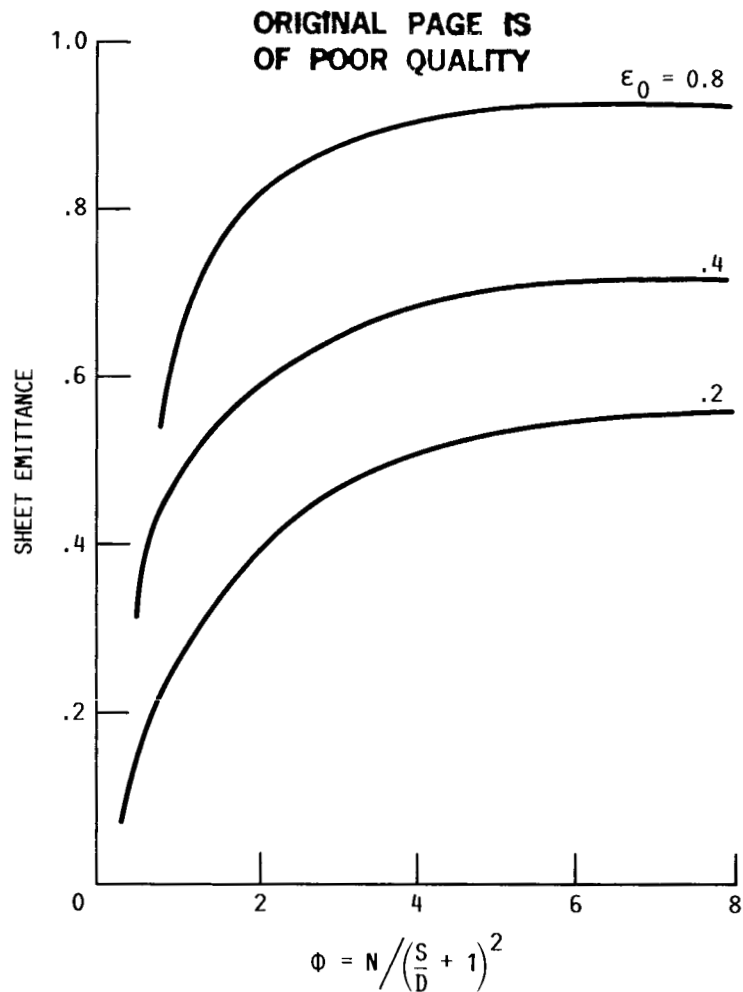


FIGURE 13. - DEPENDENCE OF SHEET EMITTANCE ON DROPLET SURFACE EMISSIVITY,  $\epsilon_0$ , AND SHEET GEOMETRY PARAMETER.

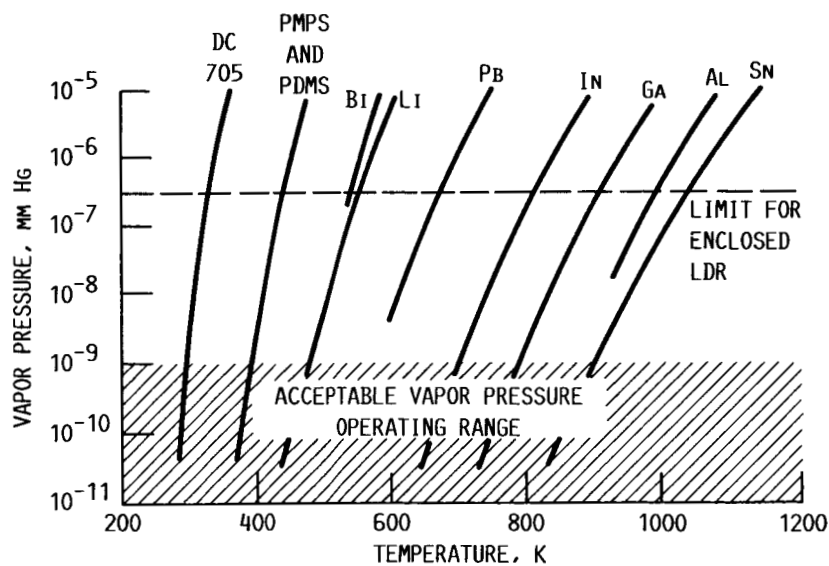


FIGURE 14. - VAPOR PRESSURES OF CANDIDATE RADIATOR FLUIDS. MAXIMUM VAPOR PRESSURE LIMITS FOR ENCLOSED AND EXPOSED RADIATORS DESIGNED FOR 30 YEAR LIFETIMES.



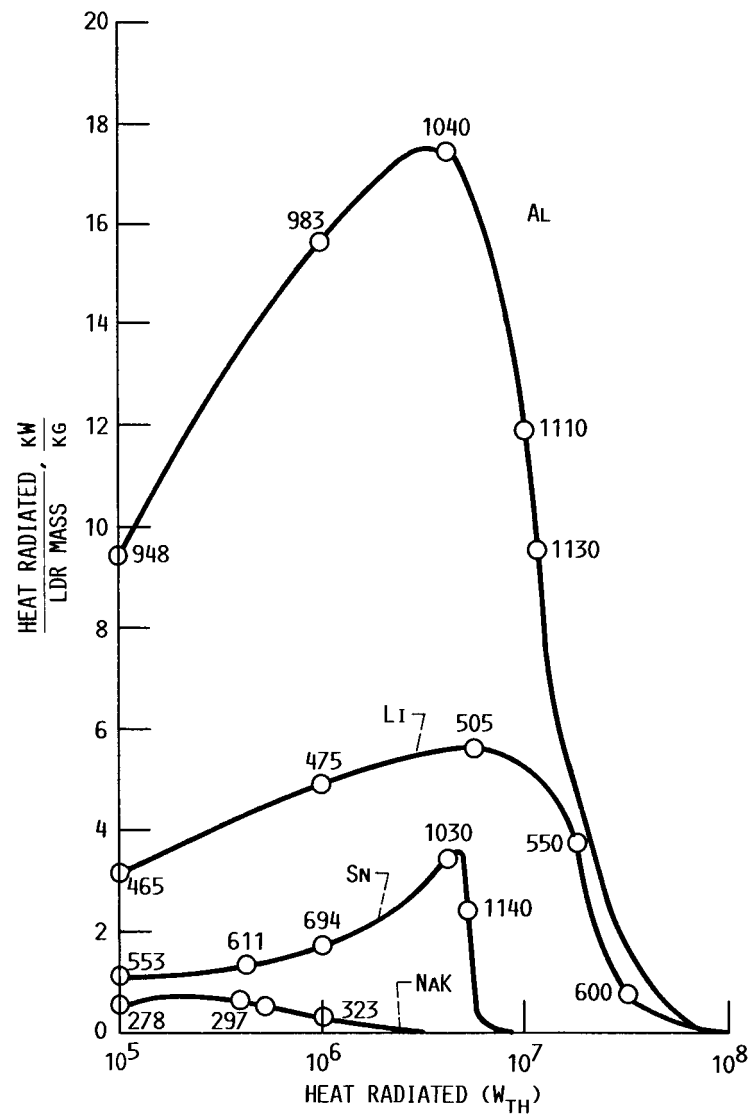


FIGURE 15. - LDR SPECIFIC POWER FOR AL, LI, SN, AND NAK WORKING FLUIDS. NUMBERS ON CURVES ARE REJECTION TEMPERATURES (IN KELVINS).

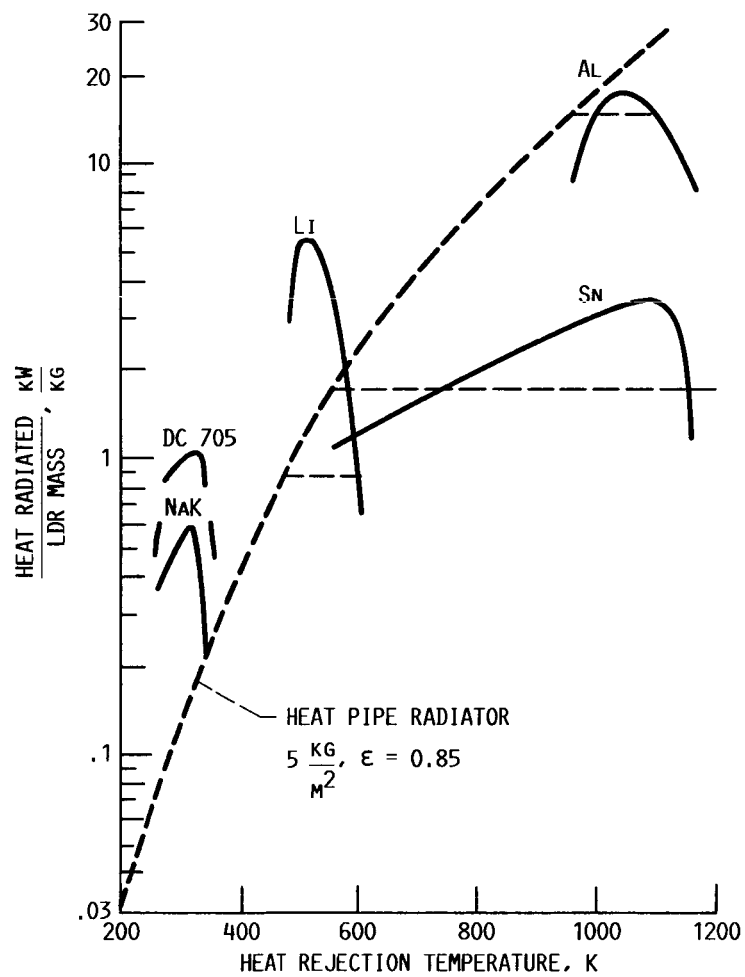


FIGURE 16. - COMPARISON OF SPECIFIC POWERS FOR LDR AND HEAT PIPE RADIATORS.

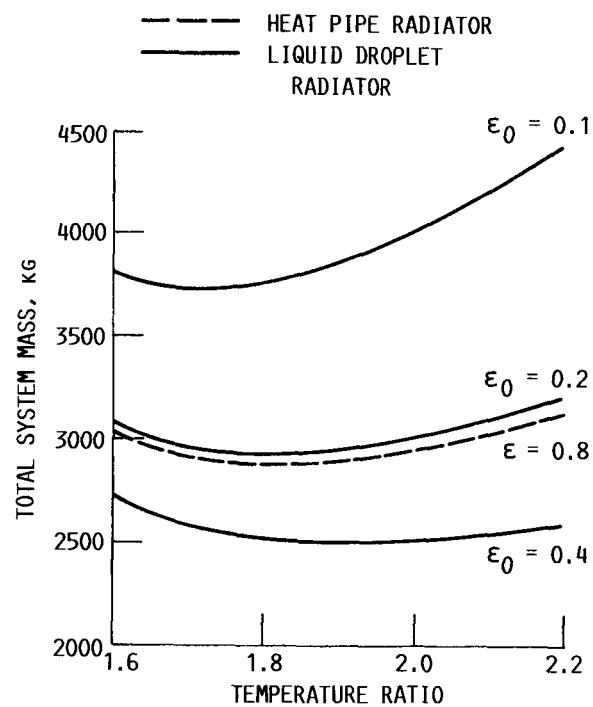


FIGURE 17. - MASS COMPARISONS FOR LDR AND HEAT PIPE RADIATOR FOR 100 kWe NUCLEAR STIRLING POWER SYSTEM.

1. Report No. <b>NASA TM-89852</b>		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle  <b>Liquid Droplet Radiator Development Status</b>				5. Report Date	
				6. Performing Organization Code  <b>505-41-5A</b>	
7. Author(s)  <b>K. Alan White, III</b>				8. Performing Organization Report No.  <b>E-3510</b>	
				10. Work Unit No.	
9. Performing Organization Name and Address  <b>National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135</b>				11. Contract or Grant No.	
				13. Type of Report and Period Covered  <b>Technical Memorandum</b>	
12. Sponsoring Agency Name and Address  <b>National Aeronautics and Space Administration Washington, D.C. 20546</b>				14. Sponsoring Agency Code	
15. Supplementary Notes  <b>Prepared for the 22nd Thermophysics Conference, sponsored by the American Institute of Aeronautics and Astronautics, Honolulu, Hawaii, July 8-10, 1987.</b>					
16. Abstract <b>Development of the Liquid Droplet Radiator (LDR) is described. Significant published results of previous investigators are presented, and work currently in progress is discussed. Several proposed LDR configurations are described, and the rectangular and triangular configurations currently of most interest are examined. Development of the droplet generator, collector, and auxiliary components are discussed. Radiative performance of a droplet sheet is considered, and experimental results are seen to be in very good agreement with analytical predictions. The collision of droplets in the droplet sheet, the charging of droplets by the space plasma, and the effect of atmospheric drag on the droplet sheet are shown to be of little consequence, or can be minimized by proper design. The effect of atmospheric drag on a droplet sheet can also be minimized with proper design. The LDR is seen to be less susceptible than conventional technology to the effects of micrometeoroids or hostile threats. The identification of working fluids which are stable in the orbital environments of interest is also described. Methods for reducing spacecraft contamination from an LDR to an acceptable level are discussed. Preliminary results of microgravity testing of the droplet generator are presented. Possible future NASA and Air Force missions enhanced or enabled by a LDR are also discussed. System studies indicate that the LDR is potentially less massive than heat pipe radiators. Planned microgravity testing aboard the Shuttle or Space Station is seen to be a logical next step in LDR development.</b>					
17. Key Words (Suggested by Author(s))  <b>Liquid droplet radiator Multimegawatt power Advanced space radiator</b>			18. Distribution Statement  <b>Unclassified - unlimited STAR Category 18</b>		
19. Security Classif. (of this report)  <b>Unclassified</b>		20. Security Classif. (of this page)  <b>Unclassified</b>		21. No. of pages  <b>27</b>	
				22. Price*  <b>A03</b>	